# OUR FOOD IN THE ANTHROPOCENE:
# THE EAT-LANCET COMMISSION ON HEALTHY DIETS FROM SUSTAINABLE FOOD SYSTEMS

Walter Willett, Johan Rockström, Brent Loken, Marco Springmann, Tim Lang, Sonja Vermeulen, Tara Garnett, David Tilman, Amanda Wood, Fabrice DeClerck, Malin Jonell, Michael Clark, Line Gordon, Jessica Fanzo, Corinna Hawkes, Rami Zurayk, Juan A. Rivera, Wim De Vries, Lindiwe Sibanda, Ashkan Afshin, Abhishek Chaudhary, Mario Herrero, Rina Agustina, Francesco Branca, Anna Lartey, Shenggen Fan, Beatrice Crona, Elizabeth Fox, Victoria Bignet, Max Troell, Therese Lindahl, Sudhvir Singh, Sarah Cornell, Srinath Reddy, Sunita Narain, Sania Nishtar, Chris Murray

***2 July 2018***

## Executive Summary

Food has the potential to nurture human health and support environmental sustainability. Instead, our food is threatening both. The challenge before us is to provide a growing global population with healthy diets from sustainable food systems. While global food production of calories has generally kept pace with population growth, approximately 800 million people still lack sufficient food, and many more consume low-quality diets that result in micronutrient deficiencies and contribute to an alarming rise in obesity and diet-related non-communicable diseases (NCDs). Unhealthy diets now pose a greater risk to morbidity and mortality than unsafe sex, alcohol, and drug and tobacco use combined. With much of the world's population inadequately nourished and many of the environmental systems that regulate the state of the planet pushed beyond safe boundaries by food production, the need for a global transformation of the food system is urgent.

The EAT-Lancet Commission *Our Food in the Anthropocene: Healthy Diets from Sustainable Food Systems* brings together more than 20 experts in various fields of human health and environmental sustainability to develop global scientific targets based on the best evidence available for healthy diets and sustainable food production. These global targets define a safe operating space for food systems that allow us to evaluate which diets and food production practices together will help ensure that the UN Sustainable Development Goals (SDGs) and Paris Agreement are achieved. Currently, lack of scientific targets for achieving healthy diets from sustainable food systems has hindered large-scale and coordinated efforts to transform the global food system.

A first step in the work of the Commission was to describe quantitatively a universal healthy reference diet to provide a basis for estimating the health and environmental impacts of adopting an alternative to current diets. Scientific targets for healthy diets, are presented in Table 1, based on the extensive literature on foods, dietary patterns, and health outcomes. It is composed largely of vegetables and fruits, whole grains, legumes, nuts, and unsaturated oils; low to moderate consumption of seafood and poultry; and zero to low consumption of red meat, processed meat, added sugar, refined grains, and starchy vegetables. Currently, the average intake of healthy foods is far below recommended levels while overconsumption of unhealthy foods is increasing. This is contributing to a rising prevalence of obesity and diet-related NCDs, including coronary heart disease, stroke and diabetes. Using several approaches, we found with a high level of certainty that global adoption of the reference dietary pattern would provide major health benefits, including a large reduction in total mortality.

**Scientific Targets for Healthy Diets***

| Food group | Food subgroup | Reference diet (g/day) | Possible ranges (g/day) |
|---|---|---|---|
| **Whole Grains** | All grains | 232 | 0 to 60% of energy |
| **Tubers/Starchy Vegetables** | Potatoes, cassava | 50 | 0 to 100 |
| **Vegetables** | All vegetables | 300 | 200 to 600 |
| **Fruits** | All Fruits | 200 | 100 to 300 |
| **Dairy Foods** | Dairy Foods | 250 | 0 to 500 |
| | Beef, lamb, pork | 14 | 0 to 28 |

| | | | |
|---|---|---|---|
| **Protein Sources** | Chicken, other poultry | 29 | 0 to 58 |
| | Eggs | 13 | 0 to 25 |
| | Fish | 28 | 0 to 100 |
| | Dry beans, lentils, peas | 50 | 0 to 100 |
| | Soy | 25 | 0 to 50 |
| | Nuts | 50 | 0 to 75 |
| **Added fats** | Unsaturated oils | 40 | 20-80 |
| **Added sugars** | All sweeteners | 31 | 0 to 31 |

* See Table 1 for a complete list of scientific targets for a 2500 kcal/day healthy reference diet

The Commission has integrated, with the quantification of universal healthy diets, global scientific targets for sustainable food systems. The objective is to provide scientific boundaries to reduce environmental degradation arising from food production at all scales. The quantification of scientific targets for the safe operating space of food systems in the world, was done for the key environmental systems and processes where food production plays a dominant role in determining the state of the planet. There is strong scientific evidence that food production is among the largest drivers of global environmental change due to its contributions to greenhouse gas (GHG) emissions, biodiversity loss, freshwater use, eutrophication, and land-system change (as well as chemical pollution, which is not assessed by this Commission). In turn, food production depends upon the continued functioning of these biophysical systems and processes in regulating and maintaining a stable Earth system. These systems and processes thereby provide a necessary set of globally systemic indicators of what constitutes sustainable food production. The Commission concludes that these quantitative scientific targets for sustainable food systems, constitute universal and scalable planetary boundaries for the food system, (Table 2). However, the uncertainty range for these food boundaries remain high, due to the inherent complexity in Earth system dynamics from local ecosystems to the functioning of the biosphere and the climate system.

**Scientific Targets for Sustainable Food Production**

| Earth system process | Control variable | Boundary | Uncertainty Range |
|---|---|---|---|
| Climate change | GHG ($CH_4$ and $N_2O$) emissions | 5 Gt $CO_2$-eq $yr^{-1}$ | (4.7-5.4 Gt $CO_2$-eq $yr^{-1}$) |
| Nitrogen cycling | N application | 90 Tg N $yr^{-1}$ | (65-90 Tg N $yr^{-1}$)<br>(90-130 Tg N $yr^{-1}$) |
| Phosphorus cycling | P application | 8 Tg P $yr^{-1}$ | (6-12 Tg P $yr^{-1}$)<br>(8-16 Tg P $yr^{-1}$) |
| Freshwater use | Consumptive water use | 2,500 $km^3$ $yr^{-1}$ | (1000-4000 $km^3$ $yr^{-1}$) |
| Biodiversity loss | Extinction rate | 10 E/MSY | (1-80 E/MSY) |
| Land-system change | Cropland use | 13 M $km^2$ | (11-15 M $km^2$) |

Diets provide an inextricable link between human health and environmental sustainability. The scientific targets for healthy diets and sustainable food systems are integrated into a common framework (i.e. safe operating space for food systems) so that "win-win" diets (both healthy and environmentally sustainable) can be identified. We propose that this framework is universal for all food cultures and food production systems in the world, with a high potential of local adaptation and scalability.

Applying this framework to future projections of world development, indicates that food systems can potentially provide the healthy diets (i.e. reference diet) for an anticipated world population of nearly 10 billion people by 2050 and still stay within a safe operating space on Earth. However, even small increases in red meat or dairy foods would make this difficult or impossible. Within the sustainable food production boundaries, the components of the reference diet can be used to make meals that are consistent with taste and dietary preferences of all regions of the world. The ranges provided within the reference diet allow for ample variation across scales and cultures in foods, production methods, and technologies as well as global dietary patterns.

Given that food systems are the major driver of poor health and environmental degradation, global efforts are urgently needed to collectively transform diets and food production. An integrative framework combined with scientific targets, as proposed by this Commission, can provide essential support for a sustainable and healthy food transformation. It is a hopeful conclusion that this Commission finds that global food systems have the potential to provide "win-win" diets to everyone on the planet in 2050 and beyond, while greatly improving health and enabling a sustainable future. However, achieving this dual aim will require a rapid adoption of numerous interventions and unprecedented global collaboration and commitment: nothing less than a Great Food Transformation.

In this report, our focus is mainly on environmental sustainability of food production and health consequences of final consumption. However, the "food system" consists of much more than these dimensions. A transformation of the global food system must ultimately involve multiple stakeholders, from individual consumers to policy makers and actors along the food value chain, working together toward the shared global goal of healthy and sustainable diets for all.

Yet, humanity has never set out deliberately to change the global food system on the scale envisioned in this report; this is uncharted policy territory and there is no magic 'fix' to the problems outlined by this Commission. Three lessons can be learned from other examples of societal responses to global changes. First, no single actor or breakthrough is likely to catalyse systems change. Transformation depends on diversity and interactions. Second, science and evidence-gathering are keys to change. Transformation depends on the fresh perspectives brought by knowledge integration. Third, a full range of policy levers, from soft to hard, will be needed. Transformation depends on shifting away from undesired activities while providing opportunities and incentives for desired actions to flourish Together, these lessons guide the thinking that will be necessary for achieving a sustainable food system transformation.

In addition, we outline five specific and implementable strategies. For each of these, there is a strong enough evidence base, and our modelling and analysis demonstrates their effectiveness for achieving a Great Food Transformation.

**Strategy one: winning international and national commitment to shift toward healthy diets**. The scientific targets set out by this Commission provide guidance about the necessary shift, which consists of high consumption of plant foods and substantially limiting animal source foods. Ample research has demonstrated that this will reduce environmental impacts and lead to better health outcomes. This concerted commitment can be demonstrated by investment in public health information and sustainability education, and better coordination between departments of health and environment.

**Strategy two: reorienting agricultural priorities away from producing 'more' food and towards producing 'better' food.** This means focusing on producing a diverse range of nutritious foods from biodiversity-enhancing food production systems rather than aiming for increased volume of a few crops, much of which is now used for animal production.

**Strategy three: sustainably intensifying food production, generating more high-quality output**. The current food system in the world is unsustainable, transgressing the scientific targets for sustainable food production within the boundaries defined by this Commission. A new agricultural revolution is required, based on sustainable intensification, and driven by sustainability and system innovation. This would entail closing yield gaps on current cropland, radical improvements in fertilizer and water use efficiency, recycling of phosphorus, redistribution of global use of nitrogen and phosphorus, implementing climate mitigation options including changes in crop and feed management, and enhancing biodiversity within agricultural systems.

**Strategy four: Stronger and coordinated governance of land and oceans.** This implies implementing a zero-expansion policy of new agricultural land into natural ecosystems and species-rich forests, management policies aimed at restoring and reforesting degraded land, establishing international land use governance mechanisms, and adopting a "Half Earth" strategy for conservation of biodiversity in intact ecosystems. Moreover, there is a need to improve the management of the world's oceans, to ensure that fisheries do not negatively impact ecosystems, fish stocks are utilized responsibly, and global aquaculture production is expanded sustainably.

**Strategy five: at least halving food losses and waste, in line with global sustainable development goals.** Substantially reducing the amount of food lost and wasted across the food value chain, from production to consumption, is essential for the global food system to stay within its safe operating space. Both technological solutions applied along the food supply chain and implementation of public policies will be needed to achieve a 50% reduction in food loss and waste.

Food will be a defining issue of the 21$^{st}$ century and unlocking its potential will catalyse pathways for global adoption of healthy diets from sustainable food systems, which is fundamental to achieving the SDGs and Paris Agreement. An unprecedented opportunity exists to develop food systems as a common thread between many ambitious international, national, and business policy frameworks aiming for improved human health and environmental sustainability goals. Establishing clear, scientific targets to guide food system transformation is an important step in realizing this opportunity.

## Conclusions

1. Unhealthy and unsustainably produced food poses a global risk for people and planet. Nearly 1 billion people in the world lack sufficient food and many more consume an unhealthy diet that contributes to premature death and morbidity. Simultaneously, global food production is the single largest human pressure on Earth, threatening local ecosystems and the stability of the entire Earth system.

2. Present dietary trends, combined with projected population growth to nearly 10 billion by 2050, will exacerbate these conditions. The global burden of non-communicable diseases is set to worsen and the impacts of food production on greenhouse gas emissions, nitrogen and phosphorus pollution, biodiversity loss, and water and land use will erode the stability of the Earth system.

3. A transformation to healthy diets from sustainable food systems is a prerequisite for attaining the UN Sustainable Development Goals and Paris Agreement, and scientific targets for healthy diets and sustainable food production are needed to guide a Great Food Transformation.

4. Healthy diets have an appropriate caloric intake and consist largely of a diversity of plant foods, low amounts of animal source foods, contain unsaturated rather than saturated fats, and limited amounts of refined grains, highly processed foods and added sugars.

5. Transformation to healthy diets by 2050 will require substantial dietary shifts, including a greater than 50% reduction in global consumption of unhealthy foods such as red meat and sugar, and a greater than 100% increase in the consumption of healthy foods such as nuts, fruits, vegetables and legumes. However, the changes needed differ greatly by region.

6. Dietary changes from current diets towards healthy diets are likely to result in significant health benefits that include averting approximately 7.4 to 10.8 million premature deaths per year, a reduction of between 18% to 28%.

7. With food production currently causing major global environmental risks, sustainable food production needs to operate within the safe operating space for food systems. This means that producing food for nearly 10 billion people should: use no additional land; safeguard existing biodiversity; reduce consumptive water use and manage water responsibly; drastically reduce nitrogen and phosphorus pollution; produce zero carbon dioxide emissions and cause no further increase in methane and nitrous oxide emissions.

8. Transformation to sustainable food production by 2050 will require at least: a 75% closing of yield gaps; a global redistribution of nitrogen and phosphorus fertilizer use; recycling of phosphorus; radical improvements in fertilizer and water use efficiency; rapid implementation of agricultural mitigation options to reduce greenhouse gas emissions and adoption of land management practices that shifts agriculture from carbon source to sink, and a fundamental shift in production priorities.

9. The scientific targets for healthy diets from sustainable food systems that we have described are intertwined across all UN Sustainable Development Goals (SDGs). In particular, this includes eradicating hunger and universal access to high quality primary health care that integrates family planning and education on healthy diets, with the SDGs on freshwater, climate, land, oceans and biodiversity and achieved through a strong commitment to global partnerships and action.

10. Achieving healthy diets from sustainable food systems for everyone on the planet will require substantial shifts towards healthy dietary patterns together with large reductions in food losses and waste and major improvements in food production practices. This universal goal is within reach but will require adoption of scientific targets by all sectors to stimulate a broad spectrum of actions from individuals and organizations working in all sectors and at all scales.

# Chapter 1 – Introduction

## Food, Planet, Health

The past 50 years have witnessed dramatic global shifts in the way food is produced and in dietary patterns. The focus on increasing crop yields and improving production practices contributed to reductions in hunger, improved life expectancy, falling infant and child mortality rates, and decreased global poverty levels.[1] These health benefits, however, are being offset by global shifts to unhealthy diets that are high in calories and in heavily-processed and animal source foods. These trends are driven partly by rapid urbanization, increasing incomes, and limited accessibility of nutritious foods.[2,3] Transitions to unhealthy diets are not only increasing the burden of obesity and diet-related non-communicable diseases (NCDs), but are also contributing to environmental degradation.[4,5] As such, our food in the Anthropocene represents one of the greatest health and environmental challenges of the twenty-first century.

**#### Insert Panel 1 – Glossary ####**

Significant steps have been taken to improve nutrition in recent decades. Yet the shortcoming of these advancements is evident because wide-scale undernutrition still exists, now alongside rising overweight, obesity and accompanying NCDs; low dietary quality contributes to both and has caused persistent micronutrient deficiencies. Globally, 815 million people remain undernourished,[6] 155 million children are stunted, 52 million children are wasted,[7] and over 2 billion individuals are micronutrient deficient.[8] At the same time, diseases associated with high-calorie, unhealthy diets are becoming more prevalent, with 2.1 billion adults overweight or obese[9] and the global prevalence of diabetes nearly doubling in the last 30 years.[10,11] Today, unhealthy diets are the largest global burden of disease,[12] and pose a greater risk to morbidity and mortality than unsafe sex, alcohol, drug and tobacco use combined.[3] With much of the world's population inadequately nourished, in terms of under-, over- and malnutrition, there is an urgent need to greatly transform our diets.

Today, food production constitutes the single largest cause of global environmental change. Agriculture occupies nearly 40% of global land,[13] and food production is responsible for up to 30% of global greenhouse gas (GHG) emissions[14] and 70% of freshwater use.[15-17] The destruction of natural ecosystems to croplands and pastures is the single largest factor causing species to be threatened with extinction.[18] Overuse and misuse of nitrogen (N) and phosphorus (P) causes eutrophication and dead zones in lakes and coastal zones.[19,20] The environmental burden from food production also includes marine systems. Almost 60% of world fish stocks are fully fished, more than 30% overfished, and global marine fisheries catch has been declining since 1996.[21,22] In addition, the rapidly expanding aquaculture sector can have negative impacts on coastal habitats.[23] Faced with the challenge of feeding nearly 10 billion people a healthy and sustainable diet by 2050, and with a rising number of environmental systems and processes that regulate the state of ecosystems and the Earth system being pushed beyond planetary boundaries by food production, there is an urgent need to radically rethink how we produce food.

## An integrated agenda for food systems

Diets are a major link between human health and environmental sustainability.[4,5] Certain “lose-lose” diets[24] or those that are unhealthy and environmentally unsustainable are often characterized as being high in calories, added sugars, saturated fats, highly processed foods and red meats. In addition, the environmental degradation resulting from these “lose-lose” diets may further compound poor health. This includes premature deaths caused by poor air quality from biomass burning for agriculture and land clearing;[25] reduced food security resulting from lower yields due to changing climactic conditions;[26] diminished nutrient content of some crops in response to rising atmospheric $CO_2$ concentrations;[27-32] and famine exacerbated by extreme weather events such as drought.[6] This Commission focuses mainly on the link between diet, human health and environmental sustainability, while several other Lancet Commissions have explored additional dimensions including the Rockefeller-Lancet Commission on Planetary Health[1], the Lancet Commission on Health and Climate Change,[33] and the Lancet Commission on Pollution and Health.[34]

Given the impact that current food systems are having on human health and environmental sustainability, nothing short of a transformation of the global food system is needed to begin reversing current trends. This transformation, however, will not be achieved without a paradigm shift in how we view and engage with food systems. This paradigm shift must recognize the inextricable link between human health and environmental sustainability and integrate these separate concerns into a common global agenda to achieve healthy diets from sustainable food systems. The call for an integrated agenda has existed since the 1980s[35], and it is in this tradition that the EAT-Lancet Commission places the concept of integrated human health and environmental sustainability at the centre of our work.

Two major global agendas have human health and environmental sustainability at their core. The UN Sustainable Development Goals (SDGs) [36] seek to end poverty, protect the planet, and ensure prosperity for all. This ambitious and inclusive international policy framework includes human health or environmental sustainability in most of its goals. The Paris Agreement, although centrally focused on climate change, also acknowledges the “right to health” and the need for climate action for human health. Furthermore, reaching the Paris Agreement of keeping global warming well under 2°C with a focus on 1.5°C, is not possible only by decarbanising the global energy system, it also requires a transition to food systems that can provide negative emissions (function as major carbon sink, instead of today being a major carbon source), and sustaining carbon sinks in natural ecosystems. Integral to the Paris Agreement is the requirement of a human health and environmental sustainability food revolution.[37,38] Given the disproportionate impact of food systems on human health and environmental sustainability, these global agendas provide an unprecedented opportunity for catalysing the paradigm shift that will be necessary to transform the global food system.

## Defining a safe operating space for food systems

An integrated human health and environmental sustainability agenda alone will not be enough to achieve the SDGs and the Paris Agreement. Clear scientific targets that define healthy diets and sustainable food production are necessary to guide policy makers, business and all food system actors. For climate we have scientific targets, provided by the Intergovernmental Panel on Climate Change (IPCC), defining ranges of maximum $CO_2$ emissions allowed to stand a chance of remaining under different levels of average mean global temperature rise. This has provided the world with estimates of remaining carbon budgets and of climate risks for societies, which in turn formed the basis for the Paris Agreement, ratified by 195 nations, of limiting global warming to well below 2°C with an aim of keeping warming to 1.5°C. However, the 1.5-2°C Paris range are science-based targets, agreed upon through negotiations and political consensus, building on the latest scientific understanding. For the global food system, clear scientific targets currently do not exist. This is a barrier for policy makers and businesses looking for guidance in achieving their food-related SDG goals and commitments under the Paris Agreement.

We can conceptualize an integrated human health and environmental sustainability agenda for the global food system that has clear scientific targets using the concept of a safe operating space for food systems. The concept of a “safe operating space” for humanity, proposed by Rockström et al. in 2009,[39] originates from the planetary boundaries framework and is defined as “global biophysical limits that humanity must operate within to ensure prosperity for future generations”.

Here we use the planetary boundaries framework as a guide to propose a safe operating space for food systems that encompasses both human health and environmental sustainability. This space is defined by scientific targets that set the lower and upper boundaries (i.e. 100 to 300 g/day of fruit) for various food groups to ensure human health (see Table 1) and planetary boundaries for food production to ensure a stable Earth system. This includes the total global amount of cropland use, biodiversity loss, water use, GHG emissions and N and P pollution that can result from food production (see Table 3). Together, these boundaries for human health and food production identify the safe operating space within which food systems should collectively operate to ensure that a broad set of human health and environmental sustainability goals are achieved.

The boundaries that define a safe operating space for food systems are not hard-fast “cliff edges” within which is safety while beyond them lies instantaneous catastrophe. The Earth system and human health are complex adaptive systems, characterized by interactions and feedbacks, which science is still trying to unveil and improve precision on. All scientific targets for a safe operating space for healthy diets and sustainable food production, are therefore associated with uncertainty. Applying a precautionary and risk perspective, the boundaries are placed at the lower end of the scientific uncertainty range, establishing a "safe space" which, if transgressed, pushes humanity into an uncertainty zone of rising risks[32]. These boundaries should therefore be viewed, not as hard thresholds, but as guides for decision makers on acceptable levels of risk for human health and environmentally sustainable food production. Operating outside this space for any Earth system process (e.g. high rates of biodiversity loss) or food group (e.g. insufficient vegetable intake) increases the risk for harm to human health and the stability of the Earth system. When viewed together as an integrated human health and environmental sustainability agenda, “win-win” diets,[24] that fall within the safe operating space for food systems, will help us to simultaneously achieve global human health and environmental sustainability goals.

## Scope and Limitations of the Commission

The EAT-Lancet Commission *Our Food in the Anthropocene: Healthy Diets from Sustainable Food Systems* brings together scientists from several disciplines to assess the current unsustainability of the global food system and set global scientific targets for shifting the world to healthy diets and sustainable food production. Given the challenge of setting scientific targets for healthy diets and sustainable food production, this Commission focused on the two “end-points” of the complex global food system; final consumption (healthy diets) and production (sustainable food production). These factors have disproportionate impact on human health and environmental sustainability. In no way does this imply that the food system is only about these two “end-points” and that the problems and solutions lie solely here.

Throughout the report we have used the term “food system” while acknowledging that food systems are much more than food production and food consumption. More broadly, they are comprised of *“all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food.”*[15] In fact, by referring to the “food system” throughout the report, our intention is to emphasize that the Great Food Transformation that we envision can only be achieved with all actors in all parts of the food system working collectively toward this transformation.

Furthermore, we acknowledge that the effects of food systems reach beyond environmental and human health impacts to include social, cultural, economic and animal welfare consequences and more. However, given the breadth and depth of the topics discussed in the report, it was necessary to place many important economic and social issues out of the scope of the Commission. These and other issues must eventually be considered to achieve healthy diets from sustainable food systems.

This Commission is not setting actionable science-based targets on behalf of any country, sector or business, nor does it have a mandate to do so. This Commission is an independent scientific body that is using the latest available science to make a global assessment of the food system and set global scientific targets for healthy diets and sustainable food production. In proposing these targets, however, we should not let the perfect become the enemy of the good.

These targets form the first attempt in providing scientific guidance for a transformation towards healthy and sustainable food systems. The task moving forward, in the absence of an IPCC or Paris Agreement for food, is for science to continue to improve definitions of global scientific targets for human health and environmentally sustainable food production while business and policy makers begin the work of translating them into operational science-based targets for various sectors, regions, and countries.

The planetary boundaries framework, which serves as a guide throughout the report, is useful because it expands the definition of sustainable food production to include the global nature of food production's environmental impacts, connecting scales from local to global. It does not, however, provide a ready-made blueprint for translation of global targets to national and sub-national governments, business, and other local actors. We frame the need for these global targets in terms of the complex system understanding that the planetary boundaries framework represents. This is intended to complement national, sectoral, sociopolitical targets and prioritizations, pointing to the global environmental context within which these diverse activity areas must fit. This becomes a first step in connecting a planetary perspective with context-specific levels of action.

In this Commission, we do not propose a magic global fix to the problems discussed. Instead, the safe operating space for food systems, as defined by this Commission, will require implementation of a variety and multitude of solutions and innovations to achieve healthy diets from sustainable food systems. For food production, we avoid comparison of specific production systems (e.g. organic versus conventional) because numerous comparisons exist[40,41] and also because debates over specific production systems and diets can be overly prescriptive and mask the diversity of contexts and available solutions. For dietary patterns, we give guidance on healthy diets, yet provide sufficient scope for many global dietary patterns (e.g. vegetarian, pescetarian, etc.) to be considered. This scope is captured both in the use of broad food groups and intake ranges that allow for various dietary preferences to be considered. Silver-bullet solutions neither exist nor would allow diverse users of this analysis to adopt a holistic concept of a safe operating space for food systems that will be needed.

Lastly, this Commission does not explore various population growth scenarios, such as the Shared Socioeconomic Pathways (SSPs). A major driver of increasing requirements for food is a rising global population, which is expected to be between 8.5 to 10 billion people by 2050. Given this, long term population stabilization will be essential for achieving healthy and sustainable diets for the world's population. Universal access to sexual and reproductive health-care services, including for family planning, information and education will be necessary components of this goal. The analysis done by this Commission follows the SSP2 for population growth, which assumes a "middle of the road" world where trends broadly follow historical patterns. The assumptions of this and other SSPs are outlined in more detail in Supplementary Table 1.

## Treatment of uncertainty by this Commission

Few decisions about diet, human health, and environmental sustainability can be made on the basis of absolute certainty because evidence is incomplete, imperfect, and continually evolving. As such, certainty must be considered as a continuum. The estimates presented in this report are based on the best available science, and we acknowledge that uncertainty exists. Therefore, when possible, we acknowledge this uncertainty and our confidence in the validity of our findings and qualitatively discuss this throughout the report "based on the type, amount, quality, and consistency of evidence".[42] In general, we have a higher level of scientific certainty about the overall direction and magnitude of the relationships described in this report, while there is considerable uncertainty around the detailed quantifications. Modeling and sensitivity analysis provided ways to explore the implications of this uncertainty.

# Chapter 2 – Healthy Diets

## What is a heathy diet?

Defining healthy dietary patterns is important for many reasons. For instance, they are used to provide dietary guidance to a population, to provide assessment and counseling in clinical settings, to develop practices and policies designed to enhance diet, and to monitor trends in diet quality for an individual or population. However, practical considerations make defining a global healthy diet challenging. This includes the different nutritional needs of people due to age, sex, disease status and physical activity levels, and needs of vulnerable populations.

A healthy diet should optimize health, defined broadly by the WHO, as being a state of complete physical, mental, and social well-being and not merely the absence of disease.[43] Here we focus on diets for generally healthy individuals two years of age and older. Young children have unique requirements to support rapid growth and development, but their diets have only minor impacts on food systems because they are a small proportion of a stable population and have low absolute energy requirements. Because animal source foods can have important influences on both human health and environmental sustainability, particular detail will be given to these foods. However, the conclusions of this chapter are based only on health outcomes. Although important, we do not consider food safety (i.e. microbial or other forms of contamination).

We define a healthy diet using food groups while taking into consideration nutritional adequacy [44] because this most directly connects food production and health, and because most dietary guidelines are based primarily on food groups. However, a focus exclusively on foods does not incorporate added fats, sugar, salt, and other constituents, so these will also be considered. The definition of a healthy diet is based on evidence from controlled feeding studies in humans with intermediate risk factors as outcomes, observational studies, randomized trials. Where available, we cite systematic reviews, meta-analyses and pooled analyses of primary data (see Supplementary Table 2 for a summary of cited references). Extensive reviews documenting the importance of dietary quality have been published elsewhere.[45,46]

The healthy dietary pattern we propose here consists of ranges of intakes for each food group. This allows for a flexible global application of these criteria, using with the specific foods and amounts tailored to the preferences and culture of different populations (see Panel 3).

## Uncertainty in estimates of a healthy diet

As described below, we have a very high level of confidence, based on many reproducible lines of evidence, that the reference diet that we have defined will meet nutritional requirements for older children and adults, and result in low rates of NCDs and overall mortality. The optimal amounts of each food group are often less clear in part because they depend on intakes of other dietary components. Also, for some food groups, the relation between intake and health risks is approximately linear, making specification of an optimal intake difficult. Although a linear positive association would suggest an optimal intake of zero, an effect of zero intake is not possible to distinguish from that of a small intake. Further, all the food groups in a diet need to fit within a constrained total energy intake. To make calculations possible for total nutrient intakes, health effects, and environmental impacts for overall diets, we provide a number for each food group of the healthy reference diet. We also provide an uncertainty range (upper and lower limits) which appears to be compatible with optimal health and also within the consumption ranges of at least some populations globally as this provides some, but limited, evidence of long term safety. In subsequent analyses, we use alternative values for some key food groups for sensitivity analyses. Using several approaches, we provide estimates of the impact of the reference diet on premature mortality. We anticipate further research will provide greater precision in defining ranges for optimal intakes of specific food groups and the health impacts of overall diets.

## Current status of knowledge

### Energy and energy balance

The global average per capita energy intake has been estimated as 2370 kcal per day at current body weights.[47] There are also gender differences. In a rigorous and large pooled analysis of US adults, energy intake was approximately 2800 kcal per day for men, and 2000 to 2200 for women.[48] These numbers would be lower in populations with lower body size and higher in populations with greater physical activity. Given these data, we have used a round number of 2500 kcal per day as a basis for different isocaloric dietary scenarios (i.e. having similar caloric values). Consuming 2500 kcal/day corresponds to the average energy needs of a 70 kg 30-year old male and a 60 kg 30-year old female with a moderate to active level of physical activity.[49] This figure is higher than the range of 2100-2300 kcal/day used in other analyses that assumed a body mass index (BMI) of approximately 22 kg/m$^2$, which is substantially lower than current reality. Although an average BMI of 22 would be healthier than current population averages, effect means of reversing the obesity epidemic have not been identified. Thus, assuming this BMI and a lower energy intake is risky and would leave little room for public health goals to increase physical activity as this will require some additional food energy. While the use of different numbers for energy intake would affect absolute required food production, it would minimally affect conclusions regarding relative effects of different dietary scenarios on environmental or health outcomes.

## Dietary components

### Major protein sources

Adequate adult protein intake is considered to be 0.8 grams per kilogram body weight, which is 56 grams per day for a 70 kg individual or approximately 10% of energy intake.[50,51] Protein "quality" reflects the amino acid composition of the food source, and animal sources of protein are of "higher quality" than most plant sources. This is particularly important for growth of infants and young children, and possibly in elderly persons who are losing lean mass.[52] However, a mix of amino acids that maximally stimulates cell replication and growth may not be optimal throughout most of adult life because more rapid cell replication is a concern for cancer risk[53]

Protein may have indirect beneficial metabolic effects by replacing excessive carbohydrate intake, especially if this is refined starch and sugar. In a large controlled feeding trial,[54] replacing carbohydrate isocalorically with protein reduced blood pressure and improved blood lipids. Similar effects were seen with monounsaturated fat replacing carbohydrate, suggesting that the benefits were due to a reduction in carbohydrate.

Because protein is consumed as part of foods that contain fat and many other constituents that influence health, it is most useful to consider protein food sources, or packages, rather than protein *per se,* when investigating or making food choices. Although most foods contain some protein, meat, dairy, fish, eggs, legumes including soy, and nuts including peanuts are relatively high in protein and often considered as alternatives in many culinary traditions. These major protein sources are also commonly used to define diets, such as omnivore, vegetarian, pesco-vegetarian, or vegan.

In a major review, the 2015 U.S. Dietary Guidelines Advisory Committee[45] concluded that for persons over two years of age, a balanced vegetarian diet can be a healthy eating pattern. In the largest prospective study of vegetarian diets, those following vegan, lacto-ovo, pesco-vegetarian, or semi-vegetarian diets together had a 12% lower overall mortality risk compared to omnivores; the lowest risk was among pesco-vegetarians.[55] Using another approach, a plant-based dietary score, giving positive values to the frequency of plant products (especially healthy plant-based foods, but not refined grains) and negative values to animal products, was associated linearly with lower risk of type 2 diabetes and coronary heart disease.[56,57] These findings suggest that a shift towards a dietary pattern emphasizing whole grains, fruits, vegetables, nuts, and legumes without necessarily becoming a strict vegan, will be beneficial.

Until recently, most analyses of specific foods high in protein and health outcomes have not specified any comparison food. Thus, in an isocaloric analysis, the comparison becomes the mix of foods comprising the rest of the diet, to which refined carbohydrates (e.g., white bread, polished rice, or corn) are typically the major contributors. Despite this limitation, in a meta-analysis of prospective studies, consumption of processed red meat (beef, pork or lamb) was associated with greater risk of death from any cause and from cardiovascular disease (CVD); unprocessed red meat was also weakly associated with CVD mortality.[58] Although the data were limited, consumption of white meat (poultry and fish) was not associated with increased mortality.  In other meta-analyses, red meat consumption was associated with risk of stroke,[59] and type 2 diabetes[60].  In two large studies of total mortality,[61-63] the relation with consumption of red meat, both processed and unprocessed, was linear and without suggestion of a threshold, suggesting that optimal intake would be very low (see Figure 1). In a pooled analysis of three large cohorts, an increment of about 35 grams/day of red meat was associated with a significant 6% increase in risk of type 2 diabetes.[64]

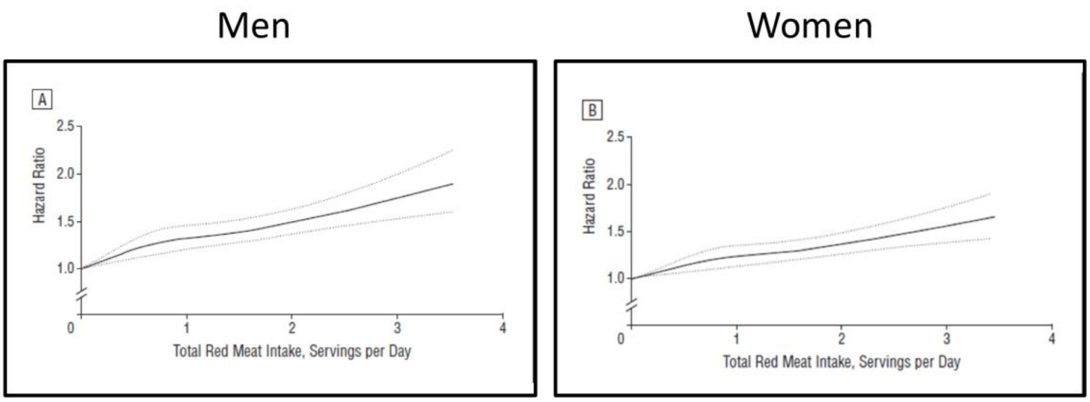


**Figure 1.** Multivariate relative risk of overall mortality (23,926 deaths) from red meat consumption during 2.96 million person-years of follow-up of 121,342 men and women. Relative risks are adjusted for age and major lifestyle and dietary risk factors. (Source: Pan et al. 2012 – permission pending)

More recently, analyses have specifically compared different protein sources in relation to risk of important health outcomes.

Although red meat consumption was only weakly associated with higher risk of coronary heart disease (CHD) when compared with the rest of the diet, red meat was more clearly associated with higher risk of CHD when specifically compared with consumption of poultry and fish, and especially nuts and legumes.[65] Similar associations have been seen in analyses with type 2 diabetes,[66] stroke,[67] and total mortality (Figure 2).[61,62] Low intake of red meat is consistent with traditional Mediterranean diets that have been associated with exceptional longevity (see Panel 3). In the 1960s, when Greek men living in Crete had very low rates of coronary heart disease and overall mortality, their average intake of red meat and poultry combined was 35 grams/day.[68]

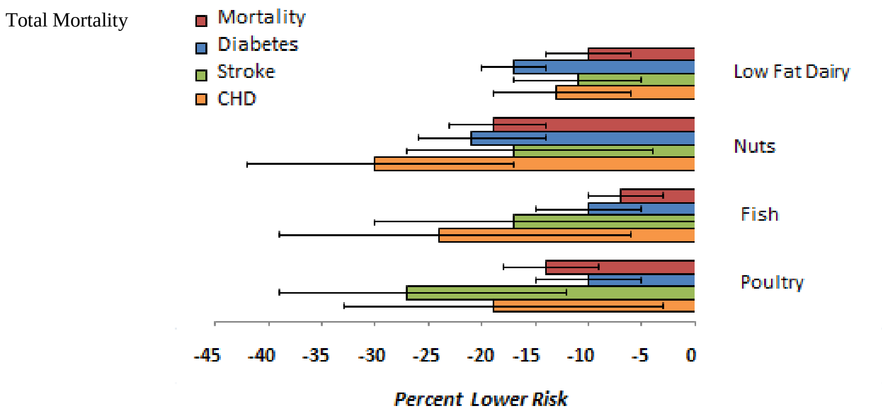


**Figure 2.** Percent reduction in risk (95% confidence interval, CI) of major health outcomes associated with replacing red meat (one serving per day) with alternative protein sources[61,62,65-67]

Based on evidence related to colorectal cancer,[69] processed red meat (e.g. treated with salt or other preservatives) was determined by the International Agency for Research on Cancer review to be a class I carcinogen, and because the data were less consistent, unprocessed red meat was a classified as a class II carcinogen.[70] Consumption of other major protein sources during midlife and later has not been clearly related to other types of cancer, although higher intake of red meat during adolescence [71] and early adult life [72] has been associated with higher risk of breast cancer.

In a recent prospective cohort analysis, protein intakes from specific food sources were examined in relation to total and cause-specific mortality among 131,000 men and women followed with repeated measures of diet for up to 32 years.[73] Replacing protein from animal sources with protein from plant sources was associated with substantially lower overall mortality. Hazard ratios were 0.66 (95% CI, 0.59-0.75) when 3% of energy from plant protein replaced an equivalent amount of protein from processed red meat and 0.88 (95% CI, 0.84-0.92) from unprocessed red meat.

The higher risks of cardiovascular disease and other outcomes associated with higher consumption of red meat are likely due in part to the dietary constituents that travel together with animal sources of protein. In particular, the higher ratio of saturated to polyunsaturated fat, heat-induced carcinogens, and heme iron, may contribute to the higher risks of cardiovascular disease diabetes, and some cancers seen for red meat compared with plant sources of protein.[63] Notably, essential polyunsaturated fatty acids comprise 4% of lipids in beef tallow, 21% in chicken fat, and 40% in salmon fat.[74] Processed meats are heterogeneous in composition but many contain high amounts of sodium, nitrates, nitrites, and other preservatives that may add to risks for cancer.

Until recently, most of the available evidence has been from European and North American studies. In a pooled analysis of Asian cohort studies, poultry and red meat consumption (mainly pork) was associated with lower all-cause mortality.[75] The discrepancies between this analysis and those from Europe and North America may be explained in part by the fact that Asian populations eat much less meat. Also noted by the authors, the findings could be due to confounding factors because meat may be more available to individuals of higher socioeconomic status, who also have better overall health. Most importantly, because many of these countries have only recently become affluent, the current levels of red meat intake do not reflect long-term intakes, like for smoking, many decades are likely needed to experience the full health consequences of high consumption. Among Chinese living in Singapore, which has been relatively affluent for several decades, red meat consumption has been associated with risk of type 2 diabetes,[76] consistent with the overall literature on this relationship.[64] However, in low income populations in which the large majority of energy is from starchy staples, the addition of meat or other major protein sources is likely to mitigate micronutrient deficiencies and have metabolic benefits by reducing the high glycemic load.

**Because intake of red meat is not essential and appears to be linearly related to higher total mortality and risks of other health outcomes in populations that have consumed it for many years, the optimal intake may be zero, especially if replaced by plant sources of protein. Because precision about risk at low intakes is limited, we conclude that a low range of intake, 0 to approximately 28 grams/day, is desirable and have used a midpoint of 14 g/day for the reference diet. As consumption of poultry, compared to red meat, has been associated with better health outcomes we have used a range of 0 to approximately 58g/day and a midpoint of 29 grams per day for the reference diet.**

High intake of dairy products, at least 3 servings per day, has been widely promoted in western counties for bone health and fracture prevention primarily because of their high calcium content,[77] but the optimal calcium intake remains uncertain. US recommendations of 1,200 mg/day are derived from balance studies lasting three weeks or less,[78] which likely reflect transient movements of calcium in and out of bone rather than long-term requirements. In a World Health Organization review, noting that regions with low intake of dairy foods and low calcium intake have lower fracture rates than regions with high dairy consumption[79] concluded that 500 mg/day is adequate and lower amounts may be adequate in areas with low fracture rates. The UK has concluded that 700 mg/day is adequate intake.[80] These lower amounts for adequate intake have major implications for dietary recommendations because many foods contain modest amounts of calcium, and eating a wide variety of diets with no dairy foods will include 300 to 400 mg of calcium. With one 250 g serving of milk/day, which contains about 300 mg of calcium, the reference diet described below contains 718 mg/day of calcium. Although prospective studies have been somewhat heterogeneous, the overall evidence suggests that among adults no important reduction in risk of fractures with calcium intakes above 500 mg a day are observed.[81]

Data on dairy consumption during childhood and adolescence in relation to long term health outcomes are limited, but high intake has been thought to be particularly important because of skeletal growth. However, higher consumption of milk by girls during adolescence was not associated with hip fracture risk later in life, and in boys higher milk consumption was associated with higher risk of fractures.[82]

**#### Insert Panel 2 – Animal source foods in Sub-Saharan Africa ####**

The overall evidence from prospective studies does not support an important increase or decrease in risk of overall mortality or cardiovascular disease with increasing consumption of dairy foods,[83] although there is likely to be a lower risk of overall and cardiovascular mortality by replacing dairy foods with nuts and other plant sources of protein.[73] High milk consumption, likely due to its calcium content, is associated with lower risk of colorectal cancer [84] but also higher risk of prostate cancer in men,[85] especially advanced cases.[86] Some evidence suggests that yogurt may reduce risk of diabetes and weight gain.[87,88] Although low-fat dairy may be preferable to high fat dairy foods for health, nearly all the fat in milk that is produced remains in the human food supply, often as butter or cream. Thus, low-fat dairy products will have little overall effect on population health because the fat is consumed in other forms.

**Because there does not appear to be a clear relationship between intake of milk or its derivatives over the range of 0 to 500 g/day and major health outcomes, and competing risks for some types of cancer, we describe a wide range of intakes as compatible with good health. Because unsaturated plant oils provide lower risks of cardiovascular disease than dairy fat, discussed below, an optimal population diet will usually be at the lower end of this range, and we have used 250 g/day for the reference diet.**

Fish intake has been associated with lower risk of cardiovascular disease.[89-91] A unique benefit of fish is likely due to its high content of omega-3 fatty acids, which play many essential roles, including being precursors of eicosanoids, a large component of the central nervous system, a structural element of every cell of the body, and a regulator of cardiac rhythm. One comprehensive analysis estimated that eating about 2 grams per week of omega-3 fatty acids in fish, equal to about one or two servings of fatty fish a week, reduces the chances of dying from heart disease by more than one-third.[89]

Fish that are high on the food chain can bioconcentrate mercury, which has neurologic toxicity. Mercury levels are high in king mackerel, shark, swordfish, tuna and tilefish, which should be avoided by pregnant and lactating women. However, adequate intakes of omega-3 fatty acids are essential for neurodevelopment, and eating more than 2 servings of fish per week or taking fish oil supplements during pregnancy has been associated with better child cognitive performance.[92] Notably, the issue of mercury toxicity is largely avoided by consuming small fish, and omega-3 fatty acids from plant sources (specifically alpha-linolenic acid, ALA) have also been associated with lower risk of coronary heart disease.[93] The degree to which these can substitute for omega-3 fatty acids from fish for other health outcomes is important to determine, as the plant sources are more widely available.

**Because approximately 28 g/day of fish can provide essential omega-3 fatty acids and is associated with lower risk of cardiovascular disease, we have used this amount for the reference diet. We also use a range of 0 to 100 g/day because higher intakes also appear**

**to be compatible with excellent health. Plant sources of ALA can provide an alternative, but the amount required is not clear.**

Eggs are a widely available source of "high quality" protein and other essential nutrients needed to support rapid growth. Despite past concern about possible increases in risk of heart disease because of their high content of cholesterol, in large prospective studies higher consumption of eggs, up to one a day, has not been associated with higher risk of heart disease, except in diabetics.[94] Interpretation of this lack of association again must consider that the default comparison in these studies has been the rest of the typical diet, which is typically far from optimal. Thus, it is likely that iso-caloric substitution of plant protein sources for eggs would reduce risk of non-communicable diseases. On the other hand, in the context of a low income country, replacing calories from a staple starchy food with an egg can substantially improve the nutritional quality of a child's diet and reduce stunting.[95]

**We have used an intake of eggs at about 13 grams/day, or about 1.5 eggs per week, for the reference diet, but higher intake may be useful for low income populations with poor dietary quality.**

Nuts, including peanuts, are nutrient-dense and contain primarily unsaturated fatty acids, fibre, vitamins, minerals, antioxidants and phytosterols. In observational and intervention studies nut consumption has favorable effects on blood lipids, oxidative stress, inflammation, visceral adiposity, hyperglycemia, and insulin resistance.[96,97] In a meta-analysis of 25 controlled feeding studies, participants were fed an average of 67 grams/day of nuts; blood levels of LDL cholesterol, LDL/HDL cholesterol, and triglycerides were reduced in a dose-response manner.[97] In prospective studies, higher consumption of nuts has been associated with lower risk of cardiovascular disease,[98-101] type 2 diabetes, and overall mortality.[102,103] In the Spanish PREDIMED trial, those randomly assigned to eat 30 grams of mixed nuts per day as part of a Mediterranean diet experienced a 28% reduction in cardiovascular disease.[104] Despite being an energy dense food, nut consumption strongly induces satiety and is associated with no weight gain (or reduced weight) and lower risk of obesity in observational studies and clinical trials.[98]

**As an alternative to red meat, for the reference diet we use an intake of 50 grams/day of nuts, which can include peanuts and tree nuts. These and other plant protein sources are generally exchangeable, although a mix is desirable nutritionally.**

Legumes have reduced LDL-cholesterol concentrations and blood pressure in controlled feeding studies.[105] In prospective studies, consumption of legumes has been associated with lower risks of coronary heart disease [65,101] compared with red meat, although the confidence intervals have been wide due to limited legume consumption. Soybeans have a relatively high fat content, which is largely polyunsaturated and includes an important amount of the omega-3 fatty acid, alpha-linolenic acid. High amounts of phytoestrogens in soy foods have weak estrogenic effects hypothesized to block actions of endogenous estrogens, and thus reduce risk of breast cancer and other hormonally related cancers. Support for this was seen in the Shanghai Women's Health Study; soy food consumption during childhood and early adult life was inversely associated with the risk of premenopausal breast cancer.[106]

**We use a total of 50 grams dry weight/day of beans, lentils, peas and 25 grams/day of soy beans.**

Other protein sources such as insects, which are important in some traditional diets, are being considered for more widespread consumption.[107] These alternatives may have low environmental impacts but their long term health effects have not been studied. Cyanobacterium, earlier referred to as “blue-green algae” has traditionally been consumed in some cultures and has a high protein content and an amino acid profile comparable to egg.[108] In vitro meat production from cultured animal stem cells is being developed as an alternative for traditional meat.[109] The health impacts of these novel foods are unclear, but nutritional composition of in vitro meat is more readily modifiable than that of conventional meat.

### Major carbohydrate sources (grains and tubers)

Grains are currently the largest source of energy in almost all diets worldwide. Refining grains leads to major loss of nutrients and fibre, which has important health implications. With remarkable consistency, greater intake of whole grains and fibre from grain sources has been associated with lower risks of coronary heart disease, type 2 diabetes, and overall mortality.[110] Fewer studies have examined total or refined grains in relation to health outcomes, but refined grains are the major source of high glycemic carbohydrates, which have adverse metabolic effect and are related to increased risk of metabolic abnormalities, weight gain, and cardiovascular disease.[88,111] In a recent prospective international study, conducted mainly in low and middle income countries, total carbohydrate intake above approximately 60% of energy, was associated with higher total mortality.[112] In controlled feeding studies, high carbohydrate intake increases blood triglycerides levels, reduces HDL cholesterol, and increases blood pressure, especially in individuals with insulin resistance.[54,113,114] This is of great global significance because declining levels of physical activity and increasing adiposity will raise insulin resistance and exacerbate these metabolic responses to carbohydrate intake, and thus increase the risk of cardiovascular disease and diabetes.[115,116]

Potatoes, although containing substantial amounts of potassium and some other vitamins, provide a large amount of rapidly absorbed carbohydrate, or glycemic load. Daily consumption has been associated with increased risk of type 2 diabetes,[117] hypertension[118] and weight gain.[119] Globally, cassava is grown for its resilience in semi-arid conditions, but when processed into flour, as is currently being done in Africa, it has low nutritional value and high glycemic load, which would be expected to increase metabolic abnormalities, weight gain, and cardiometabolic disease.

**We use these major carbohydrate sources to maintain the target energy intake; available evidence does not support a specific percent of energy intake but keeping this below approximately 60% of energy appears desirable and whole grains are emphasized. Thus, we use 232 grams of whole grains and 50 grams of tubers and starchy vegetables per day (with a limit of 100 grams of tubers/starchy vegetables).**

### Fruits and vegetables

Fruit and vegetables are a critical source of many micronutrients, including pro-vitamin A for the prevention of night blindness. Substantial evidence indicates that fruit and vegetable consumption is also important for cardiovascular disease prevention; the large majority of benefit is achieved by consuming about 5 servings per day,[120,121] although higher intakes may provide some benefits. High intake of vegetables reduces blood pressure [122] and is associated with lower risk of type 2 diabetes.[123] Increasing intake of most non-starchy vegetables has been associated with less weight gain in long term follow-up of U.S. adults,[119] but intakes of potatoes, corn, and peas were each associated with greater weight gain. Higher fruit and vegetable consumption is weakly related to lower cancer incidence reduction after adjusting for differences in other lifestyle factors such as smoking and body mass index.[124,125]

**We use intakes of 300 grams/day of vegetables and 200 grams/person/day of fruits, or about 5 servings of fruits and vegetables each day. This appears to provide the large majority of benefit from these foods if the mix suggested is included.**

### Added fat—total and specific fatty acids and sources of fats

Added fats from animal sources (e.g., ghee, butter, lard) or plants (e.g., oils, margarines, shortening) are used in countless recipes and in cooking of many foods; they can comprise up to about 30% of total energy in some diets. Until recently, most dietary recommendations suggested reducing or limiting total fat intake to decrease risks of coronary disease and cancer. However, evidence from both prospective cohort studies and randomized trials has not supported a benefit of reducing total fat intake.[126,127] Evidence supports a substantially lower risk of cardiovascular disease by replacing saturated fat with unsaturated vegetable oils, especially those high in polyunsaturated fats that include both omega-3 and omega-6 fatty acids.[128-131] [126] Intake of *trans* isomers from partially hydrogenated oils is particularly deleterious.[132]

Although intakes of specific fatty acids have been studied extensively in relation to risk of heart disease, edible oils are always a combination of saturated, mono-unsaturated, and polyunsaturated fatty acids, depending on the source and processing. Palm and soybean oil are the most widely consumed oils globally. Palm oil is low in polyunsaturated (9% vs 60% in soybean oil) and relatively high in saturated fat (52% vs 16% in soybean oil), and is widely consumed in many low- and middle-income countries. Consistent with this fatty acid composition, consumption of industrially processed palm oil raises LDL-cholesterol compared to less saturated plant oils.[133] In a case-control study conducted in Costa Rica, consumption of industrially processed palm oil was significantly associated with greater risk of myocardial infarction compared to nonhydrogenated soy bean oil.[134] In many West African countries and parts of Brazil, minimally processed red palm oil is an important source of provitamin A due to its high beta-carotene content. Consumption of red palm oil has not been studied in relation to risk of heart disease and moderate intake may be compatible with low rates of heart disease.

In the PREDIMED trial, compared to a low-fat diet, a Mediterranean diet high in extra virgin olive oil reduced incidence of cardiovascular disease and also improved cognitive function.[104] Rapeseed oil, also called canola oil, is high in monounsaturated fats and contains a substantial amount of omega-3 fatty acid. In a randomized trial among survivors of an acute myocardial infarction, a Mediterranean-type diet high in rapeseed oil greatly reduced risk of recurrent infarction or death.[135] Also, in the most strikingly successful national program to reduce rates of coronary heart disease (Finland), rapeseed oil was used to replace dairy fat.[136] Dairy fat has one of the highest proportions of saturated fatty acids in natural foods. In a detailed prospective analysis among men and women, dairy fat was associated with greater risk of CHD when compared isocalorically to unsaturated plant oils.[137]

Low-fat diets have been widely promoted as means of losing weight or prevention of weight gain. Most of the randomized trials to support this conclusion were less than one year in duration[138] which can be misleading because initial reductions in weight are often reversed. Also, the intensity of intervention was not balanced in many trials,[139] which is important because monitoring intake and social support can lead to modest weight reductions independent of the dietary composition.[140] In a meta-analysis including over 50 randomized trials lasting at least one year, reductions in dietary fat were associated with slightly less weight loss compared with the higher-fat control diet when the intensity of intervention was similar.[141]

**Strong evidence supports consumption of plant oils low in saturated fat as an alternative to animal fats and there is no clear evidence of an upper limit. Thus, a wide range is suggested, and we use 50 grams/day of total added fat with a mix emphasizing predominately unsaturated plant oils.**

### Sugar and other sweeteners

Sugar, like refined starches, has multiple adverse metabolic effects, at high intakes may further increase plasma triglycerides.[142] Higher intakes of added sugars, especially sugar-sweetened beverages, have been associated with weight gain,[143,144] type 2 diabetes,[145] and greater cardiovascular mortality.[146] The WHO recommends that sugar intake be less than 10% of energy and suggests that reducing to 5% would provide further benefits; the American Heart Association suggests approximately 5% of energy or less.[147]

**As sugar has no nutritional value and adverse metabolic effects, we use a limit of 31 grams/person/day of all sweeteners, or less than 5% of energy.**

## Special considerations

### Young children and adolescents

Global and most regional guidelines recommend that infants should be exclusively breastfed for the first 6 months of life and continued breastfeeding until 2 years of age and beyond. Benefits include healthy growth and expected cognitive development as well as lower risk of becoming overweight or obese and developing NCDs later in life.[148,149] For children 12–23 months, whether breastfed or not, a diet with the daily inclusion of at least four of seven food groups has been recommended.[150]

Adolescent girls are at particular risk of iron deficiency because of rapid growth combined with menstrual losses. Menstrual losses have sometimes been a rationale for increased consumption of red meat, but RDA level supplements, for example as a multiple vitamin/multimineral preparation, provide an alternative that is far less expensive and without the adverse consequences of high red meat intake. The WHO suggests extra iron for female adolescents by supplementation where the prevalence of anemia is high, with extra caution in malaria endemic regions.[151]

### Healthy diets during pregnancy and lactation

During pregnancy and lactation, overall food intake is important to support organ, muscle and bone growth, as well as better physiological and metabolic health. However, excessive protein intake from animal sources has been associated with a greater risk of obesity in offspring 20 years later.[152] In a systematic review[153] consumption of dairy foods was inconsistently associated with birthweight or fetal length. Although the inclusion of some of animal source food in maternal diets is widely considered important for optimal fetal growth, and increased iron requirement, especially during the third trimester of pregnancy, limited evidence also suggests that balanced vegetarian diets can support healthy fetal development, with the caveat that strict vegan diets require supplements of vitamin B-12.[154] The WHO recommends a healthy diet during pregnancy as adequate energy, protein, vitamins and minerals, obtained through the consumption of a variety of foods, including green and orange vegetables, meat, fish, beans, nuts, whole grains and fruits.[155]

## Summary of evidence describing healthy diets

The combined evidence from controlled feeding studies with intermediate risk factors as outcomes, long-term observational studies relating individual dietary components and overall dietary patterns to major disease endpoints and quality of life,[156-158] and randomized clinical trials supports the conclusion, with a high level of certainty, that dietary patterns with the following characteristics promote low risk of major chronic disease and overall wellbeing:

- Protein sources primarily from plants, including soy foods, other legumes, and nuts. Fish or alternative sources of omega-3 fatty acids several times per week, with optional modest consumption of poultry and eggs.  Low intakes of red meat, if any, especially processed meat.
- Fat largely from unsaturated plant sources, with low intakes of saturated fats; no partially hydrogenated oils
- Carbohydrates primarily from whole grains with limited intake refined grains and sugar less 5% of energy
- At least five servings of fruits and vegetables per day, not including potatoes
- Moderate dairy consumption as an option.

These elements of a healthy diet allow great flexibility because they are compatible with a wide variety of foods, agricultural systems, cultural traditions, and individual preferences. These elements can be combined in various types of omnivore, vegetarian and vegan diets. The findings of benefits in many different populations for overall dietary patterns, such as the Mediterranean and healthful plant-based diets, document that healthy dietary patterns can be practically achieved in contemporary populations in many countries.

Given the above evidence regarding the elements of healthy diets, a healthy reference diet for 2500 kcal/day is described in Table 1, These intakes provide a starting point for further analyses to evaluate the potential for feeding the world's population a healthy diet while remaining within food production boundaries.

**#### Insert Panel 3 – Feasibility of reference diet ####**

**Table 1.** A Healthy Reference Diet, with possible ranges, for an intake of 2500 Kcal/day.[1]

| Food Group | Food subgroup, examples | Reference diet (g/day) | Kcal/ Day[1] | Possible ranges (g/day) | Comments |
|---|---|---|---|---|---|
| **Whole Grains[2]** | Rice, wheat, corn, other | 232 | 811 | Total gains 0 to 60% of energy | Mix and amount of grains can vary to maintain isocaloric intake |
| **Tubers/Starchy Vegetables** | Potatoes, cassava | 50 | 39 | 0 to 100 | |
| **Vegetables** | All vegetables | 300 | | 200 to 600 | |
| | Dark green vegetables | 100 | 23 | | |
| | Red & orange vegetable | 100 | 30 | | |
| | Other vegetables | 100 | 25 | | |
| **Fruits** | All fruit | 200 | 126 | 100 to 300 | |
| **Dairy Foods** | Whole milk or derivative equivalents (cheese, etc.) | 250 | 153 | 0 to 500 | |
| **Protein Sources** | Beef, lamb | 7 | 15 | 0 to 14 | Exchangeable with Pork |
| | Pork | 7 | 15 | 0 to 14 | Exchangeable with Beef/lamb |
| | Chicken, other poultry | 29 | 62 | 0 to 58 | Exchangeable with eggs, fish, or plant protein sources |
| | Eggs | 13 | 19 | 0 to 25 | |
| | Fish | 28 | 40 | 0 to 100 | |
| | Legumes[2] | | | | Legumes, peanuts, tree nuts, seeds, and soy are interchangeable |
| | Dry beans, lentils & peas | 50 | 172 | 0 to 100 | |
| | Soy foods | 25 | 112 | 0 to 50 | |
| | Nuts<br>- Peanuts<br>- Tree nuts | <br>25<br>25 | <br>142<br>149 | 0 to 75 | |
| **Added fats** | Plant oils<br>- Palm<br>- Unsaturated oils[3]<br>- Dairy fats (included in milk)<br>- Lard/tallow | <br>6.8<br>40<br>0<br>5 | <br>60<br>354<br>0<br>36 | <br>0-6.8<br>20-80<br><br>0-5 | Some lard or tallow optional where pigs or cattle are consumed |
| **Added sugars** | All sweeteners | 31 | 120 | 0 to 31 | |

[1] For an individual, an optimal energy intake to maintain a healthy weight will depend on body size and level of physical activity. The processing of foods such as partial hydrogenation of oils, refining of grains, and addition of salt and preservatives can strongly influence their effects on health but is not addressed in this table.

[2] Wheat, rice, dry beans and lentils are dry, raw

[3] Unsaturated oils are 20% each of olive, soybean, rapeseed, sunflower, and peanut oil

## Current dietary patterns compared to reference diet

Current global food intakes are markedly different from the reference diet in both quality and quantity (Figure 3). Globally, diets are lacking in fruit, vegetables, nuts, whole grains, legumes and fish. At the same time, global diets are high in eggs and red meat, although regional analysis indicates that diets in South Asia and Sub-Saharan Africa do not reach the levels suggested in the reference diet (Panel 2). Poultry intake exceeds the reference amount in Latin America and the Caribbean, the Middle East and Northern Africa, Europe and Central Asia and North America. Dairy consumption exceeds the reference intake in Europe, Central Asia and North America. Notably, the ranges in the reference diet allow for shifting of red meat, dairy, eggs and poultry to additional amounts of legumes, nuts, or fish to accommodate a variety of cultural or agricultural factors. Overall, the absolute average intake of most healthy foods is still below the levels in the reference diet, and the amounts of red meat, eggs, and tubers/starchy vegetables is far above the reference intake, with considerable regional variation. An analysis of trends in Mexican diets over the past several decades is a good example of how diets have changed and how current dietary patterns are often far from the reference diet (Panel 4).

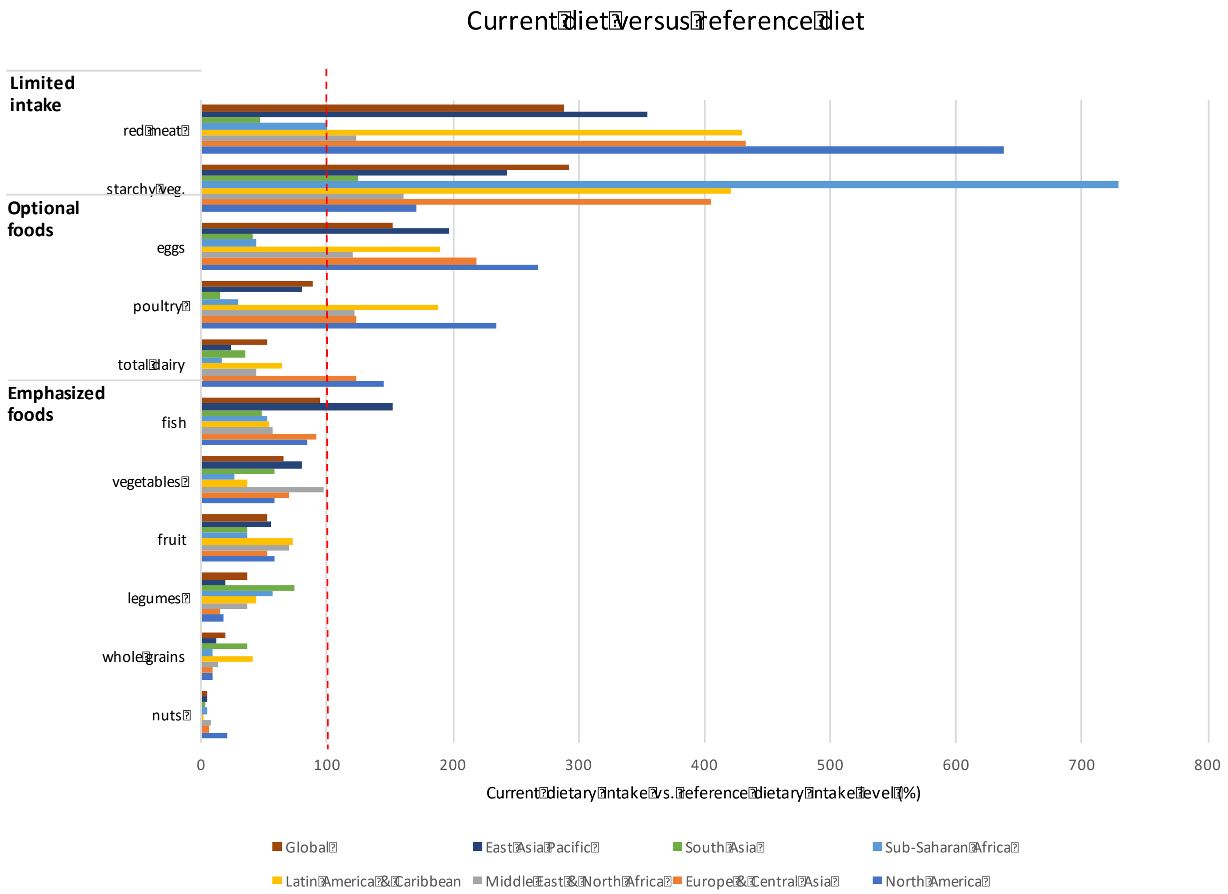


**Figure 3**. The "diet gap" between current dietary patterns and recommended intakes of food in the reference diet. Data on current intakes are from the Global Burden of Disease (GBD) database.[12]

**#### Insert Panel 4 – A dietary transition in Mexico ####**

## Analyses of total diets: nutrient adequacy and mortality

A variety of dietary patterns and dietary quality scores have been created by combining multiple elements of diet, which may have additive or synergistic effects. Although the methods to develop these scores or indices has varied, those that are similar to the reference diet (incorporating higher intakes of fruits, vegetables, whole grains, plant protein sources, and more unsaturated fats) have consistently predicted lower risks of cardiovascular risk factors and adverse health outcomes, including total mortality.[54,159-169]

For this report, we quantified the healthiness of the reference diet in two ways: assessment of nutrient adequacy and prediction of mortality rates. To assess nutrient adequacy, we first analyzed the nutrient composition of this diet using data primarily from US sources (see supplementary Table 3). We also paired country-specific food composition data and current dietary data to evaluate the effect of moving to the reference diet on nutrient adequacy. In this analysis, changes to the reference diet would improve nutrient intakes for most nutrients. Healthy fats (mono and polyunsaturated fatty acids) are increased, while unhealthy fats (saturated fatty acids) are reduced. Dietary changes towards the reference diet also improve the adequacy of most micronutrients, including several critical ones, such as iron, zinc, folate and vitamin A, as well as low calcium intake in low-income countries. The only exception is vitamin B12 which is generally low in diets that are low in animal-based ones. Supplementation or fortification with vitamin B12 (and possibly with riboflavin) might be necessary in some circumstances.[170]

We analyzed the potential impacts of dietary change on diet-related disease mortality using three different approaches (see Table 2). The first used a global comparative risk assessment framework coupled to agricultural production and consumption statistics.[5] Its risk factors included high consumption of red meat (including beef, lamb, and pork), low consumption of fruits, vegetables, legumes, nuts, and fish, and being underweight, overweight, and obese. The disease endpoints included coronary heart disease (CHD), stroke, type-2 diabetes mellitus, site-specific cancers, and an aggregate of other diseases. Relative risk factors that connect changes in dietary risks to changes in disease mortality in a dose-response manner were adopted from meta-analyses of prospective cohort studies.[59,60,69,91,101,103,121,171] Methods for this analysis can be found in the supplementary information and a full description of the methodology with sensitivity analyses used can be found in Springmann et al. (forthcoming)[172] We estimated that adopting the reference diet could lead to about 9.2 million avoided deaths (20% of all deaths among adults) when accompanied by shifts towards optimal weight levels, and to about 4.7 million avoided deaths 10% of all deaths among adults) without weight changes. Increased consumption fruits, vegetables, nuts, and legumes contributed about one million avoided deaths each, followed by reductions in red meat consumption (half a million avoided deaths), and increased fish consumption (about 270,000 avoided deaths).

Using a conceptually similar approach but somewhat different assumptions and data sources based on dietary surveys and food expenditure data, the Global Burden of Disease Collaborators estimated that deaths could be reduced by about 18% or 10.8 million deaths per year with universal adoption of a diet similar to the reference diet[173] ( see Table 2). High intakes of sodium and low intakes of whole grains and fruit contributed most to reduced mortality.

The third approach scored both the reference diet and current diets using the Alternative Healthy Eating Index (AHEI)-2010,[174,175] which has predicted lower mortality and disease risks in many populations.[176,177] This index includes lower scores or greater consumption of trans fat and sugar-sweetened beverages and higher scores for greater consumption of polyunsaturated fat in addition to variables included in the other analyses. Sex-specific relative risks relating increments in AHEI scores to total and disease-specific mortality rates were estimated using two large cohorts with many repeated assessments of diet (see supplementary information for methods). Applying these relative risks to current dietary data and disease rates for 118 countries (excluding only deaths due to trauma and infectious disease), we estimated that premature deaths could be reduced by about 28%% or 7,400,000 deaths per year by adoption of the reference diet

**Table 2.** Estimated avoided premature deaths among adults by global adoption of reference diet.

| Method | Percent | Number | Comments |
|---|---|---|---|
| **Comparative Risk Model (1)** | 20% among adults (~ 15% using GBD number of all deaths) | 9,210,000<br><br>(158 countries) | Changes in weight levels and intake of fruits, vegetables, nuts, and legumes were main contributors. |
| **GBD Model (2)** | 18.1% | 10,800,000<br>(195 countries) | High sodium intake and low intakes of fruits and vegetables were main contributors |
| **Empirical Disease Risk (3)** | 27.8% | 7, 400,000<br>(118 countries) | High intakes of *trans* fat and red/processed meat, low intakes of nuts/legumes, polyunsaturated fats and whole grains were main contributors |

1. Dietary factors included high consumption of red meat (including beef, lamb, and pork), low consumption of fruits, vegetables, legumes, nuts and seeds, fish, and being underweight, overweight, and obese.[172]
2. The Global Burden of Disease estimates[173] (manuscript in review at Lancet) are based on an “optimal diet” similar to the Reference Diet. Dietary factors included fruits, vegetables, legumes, whole grains, nuts and seeds, milk, red meat, processed red meat, sugar-sweetened beverages, fiber, calcium, marine N-fatty acids, polyunsaturated fat, trans fatty acids, sodium.
3. The Alternative Healthy Eating Index-2010[174,175] used in the analysis included vegetables (potatoes not included), fruits, whole grains, sugar-sweetened beverages/fruit juices, nuts and legumes, red meat, trans fatty acids, marine N-3 fatty acids, polyunsaturated fat, and sodium (alcohol not included).

# Chapter 3 – Sustainable Food Production

## An Earth system perspective on sustainable food production

The need to develop and adopt sustainable food production practices that safeguard Earth system processes on which both food production and human well-being depend has become widely recognized. Farming and fishing practices are being developed that better harness ecosystem services such as pest control, pollination, water regulation, and nutrient cycling to achieve productivity and resilience, while reducing harmful environmental impacts.[178] These practices include many approaches such as conservation agriculture, sustainable and ecological intensification, agro-ecological and diversified farming systems, precision agriculture and organic farming.[179-182]

Most of these practices focus on sustainability at the farm scale, including improvement of soil carbon concentrations, reduction of nutrient leakage from fields, and enhanced water use efficiency of crops. Many practices also take a landscape and/or watershed perspective, in that they aim at improving the management of ecological processes across the whole landscape in which production is embedded.[178,183] Therefore, most work on defining environmentally sustainable food production has been conducted at field to landscape levels. This is important because visible agricultural impacts are primarily local and differ across the globe, with varying soils, hydroclimates and agro-ecological zones. Thus, the methods needed for minimizing the environmental impacts of food production will vary between regions.

We have, however, now entered a new geological epoch, the Anthropocene,[184] where humanity is the dominating force of change on the planet, and where food production is the single largest source of environmental degradation and impact on the Earth system. In light of the global impacts that stem from the food system, there is rising recognition of the need to adopt an Earth system approach to sustainable food production, which can no longer be defined only in terms of reducing environmental impacts from local farming systems. In the Anthropocene, sustainable food production needs to include the role played by food production in regulating the state of ecosystems, the biosphere, and ultimately the Earth system. This means considering the complex systemic interactions from local to global scales, and identifying global boundaries within which the global food production needs to stay in order to safeguard biophysical processes that support a stable Earth system.

This widens the perspective of sustainable food production in a critical and complementary way and the large scale change to global biogeochemical cycles provides an example. At the field scale, sustainable food production can be defined from a nutrient perspective (N and P application) as a system with no nutrient leakage into local groundwater and rivers. However, N and P form part of the agricultural harvest and are transported to cities or markets often far from where they were applied. Here N and P ultimately end up either as direct nutrient pollution as food waste or untreated excreta, or as partial downstream pollution after passing through municipal sewage treatment. The end result is that a significant percentage of N and P ends up as nutrient loading in aquatic systems, causing eutrophication of freshwater systems or coastal zones often far from where it was originally applied as fertilizer. With rising human interference with the global cycles of N and P in the Anthropocene, an Earth system perspective on N and P is necessary, which translates not only to reducing environmental impacts of N and P in farmers' fields, but also to reducing the total amount of new reactive N and P being added globally from the atmosphere and mines into the biosphere.

The planetary boundaries framework is useful in expanding the definition of sustainable food production to include the global nature of food production's environmental impacts, connecting scales from local to global. The framework relates to processes in the Earth system seen from the planetary scale. A global boundary is not simply the average of regional impacts and cannot be quantified solely by focusing on regional environmental assessments. Managing systems and processes, such as those explored by this Commission, to meet local and regional needs changes planetary behaviour, and in turn, adding the planetary perspective can influence the priorities for action at regional and local scales. For example, land management decisions in one region can affect ecosystems and land cover elsewhere through changes in the water cycle and long-range pollution.[185,186] It is important to recognize the dynamic interactions across scales and between Earth system “components” (land, ocean, atmosphere, biosphere) when setting targets for transforming the food system. This perspective underpins this Commission’s initial focus on setting global scientific targets as a necessary first step.

The planetary viewpoint of Earth system science is increasingly focusing on context-specific insights from systems ecology, enabled by global modelling, worldwide observation systems and international science partnerships. This frontier research field points to critical system components and processes that regulate the behavior of the Earth system, and that are key for global sustainability (see Supplementary Table 4).[187-189] This Commission draws upon this field and has identified six systems and processes that are the main environmental systems impacted by food production, and for which scientific evidence about their Earth system behavior enables us to provide quantified scientific targets. These are: climate change, biodiversity loss, land-system change, freshwater use, and nitrogen and phosphorus flows.[190-193]

We use the planetary boundaries framework as a guide in this report because: 1) the six systems and processes quantified by this Commission are found within this framework; 2) we are setting global targets and this framework relates to Earth system process at the planetary scales; 3) this framework has already provided various countries and sectors with a useful way of holding multiple anthropogenic global environmental pressures in mind simultaneously. The framework, however, does not deal explicitly with interactions between the various Earth system processes, although it was devised with such dynamics firmly in mind.

For each process, we draw upon the available science to propose boundaries that sustainable global food production must stay within. These boundaries conceptually define the upper limit of environmental impact for food production at the global scale that decrease the risk of irreversible and potentially catastrophic shifts in the Earth system.[190,194]

**#### Insert Panel 5 - Planetary Boundaries ####**

## Uncertainty in estimates of sustainable food production

As described below, the definition of sustainable food production requires setting planetary boundaries for food production impacts on the climate system, land systems, freshwater, biodiversity, and nutrient cycles of nitrogen and phosphorus. In this chapter we present the underlying scientific rationale, literature sources, and assumptions behind each of the boundaries for our definition of sustainable food production. However, the boundary levels for each process demarcating the shift to irreversible and deleterious Earth system change are difficult to set with precision, because of scientific uncertainty, natural variability and the critical interdependencies of Earth system processes. In this report, we use uncertainty ranges, based on the scientific literature and our judgment of the level of confidence, to reflect the uncertainty that exists in setting global boundaries for sustainable food production (Table 3).

# Climate change

## Overview

Anthropogenic emissions of GHGs cause climate change, which leads to disruptions in the Earth system, such as sea-level rise and an increase in the frequency of extreme weather events.[195] Food production systems release GHGs (e.g. $CO_2$, $CH_4$, $N_2O$) into the atmosphere directly, and drive land use change that releases additional carbon dioxide ($CO_2$) as forests are cleared, wetlands drained, and soils are tilled. However, with proper management agricultural systems may also provide valuable carbon sinks that absorb $CO_2$ from the atmosphere. Food production is a prime source of methane ($CH_4$) and nitrous oxide ($N_2O$) which have respectively 56 and 280 times the global warming potential (over 20 years) of $CO_2$.[195] Methane is produced during digestion in ruminant livestock such as cows and sheep, or during anaerobic decomposition of organic material in flooded rice paddies. Nitrous oxide mainly arises from soil microbes in croplands and pastures and is influenced by soil fertility management, such as fertilizer application. Carbon dioxide is released on agricultural land from the tillage of soils and during burning to clear land of plants, soil organic matter and agricultural residues, and from burning fossil-fuels by farm machinery and in transport of agricultural products. It is also released when converting natural ecosystems, especially forests, to agriculture.

The biological processes that produce emissions are intrinsic to crop and livestock production and some level of GHGs will always be generated by biological processes intrinsically associated agriculture. Therefore, while we can and must set high ambitions for anthropogenic GHG emissions reductions (to meet the Paris climate target of < 2°C), we cannot expect to fully eliminate all GHG emissions (i.e. $CH_4$, $N_2O$) related to food production and a minimum threshold level of residual emissions has not yet been quantified. Here we propose a boundary for GHG emissions from food production, which we assess is both necessary and hard to reduce further, at least until 2050, if we want to achieve both healthy diets for everybody on the planet and the Paris Climate Agreement.

## A global carbon budget

The Paris Agreement frames the political and scientific consensus to keep the global mean temperature increase by 2100 under 2°C and if possible closer to 1.5°C, relative to 1861–1880 temperatures. To stay within this boundary, there is a maximum amount of GHGs that can still be emitted (i.e. the carbon budget). This translates to a remaining total global emissions budget from 2011 onwards of approximately 800 $GtCO_2$ for $CO_2$ or 1000 $GtCO_2$-eq for $CO_2$, $CH_4$ and $N_2O$ combined These estimates are from the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) and represents the most stringent mitigation pathway (representative concentration pathway - RCP2.6) and describes a 66% chance for limiting global warming <2°C.

The majority of scenarios underlying the RCP2.6 pathway involve overshooting the carbon budget initially and then compensating, particularly from 2040 onwards by massive removals of $CO_2$ from the atmosphere.[196] A variety of negative emissions technologies and actions could theoretically deliver these removals with the most commonly promoted approaches being carbon capture and storage (CCS) and bioenergy with carbon capture and storage (BECCS). BECCS, however, may have major implications for land use and food security (Panel 6).

#### Insert Panel 6 – Negative emissions ####

Figure 4 summarizes recent data[37] on likely requirements, in terms of global GHG emission trajectories, to reach the Paris climate target. For a 66% probability of maintaining <2°C global warming, global $CO_2$ emissions from fossil-fuel burning and industrial processes must peak no later than 2020 and then reach a residual of ~5 $GtCO_2\ yr^{-1}$ by 2050. Land Use, Land-Use Change, and Forestry (LULUCF) emissions, dominated by agricultural expansion and agricultural land use emissions, will have to transition by 2050 from a net global source (currently ~5 $GtCO_2\ yr^{-1}$) to a net carbon sink (-10 $GtCO_2\ yr^{-1}$) by 2100.

Given this, how food is produced is central to whether or not the Paris climate target of <2°C is attainable. This will involve minimizing non-$CO_2$ emissions, in particular $CH_4$ and $N_2O$, from food production and transforming the world's food production systems from net carbon sources to net carbon sinks. In addition, achieving the Paris target will also require the rapid global decarbonisation of the energy system.

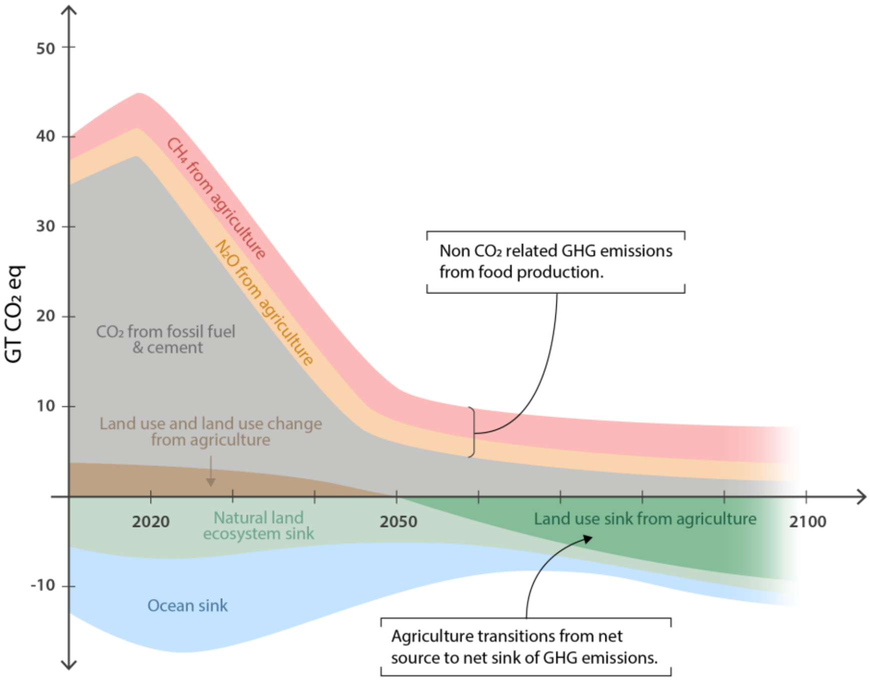


**Figure 4.** Assessment of global emission trajectories to have a chance of reaching the Paris climate target of < 2° C global warming, with a particular focus on the role of the global food system. Data from IPCC AR5 (RCP2.6 data for $N_2O$ and $CH_4$) and Rockström et al.[37] (for fossil-fuel emissions, LULUCF, and biosphere carbon sinks).

## Current status of emissions associated with food production

Estimates of agriculture's net GHG emissions vary widely depending on which subcategories are included: (1) emissions of non-$CO_2$ gases ($CH_4$ and $N_2O$) from agricultural production are estimated to be 5.0-5.8 Gt $CO_2$-eq $yr^{-1}$ [197]; (2) $CO_2$ emissions from conversion of natural ecosystems, especially forests, to croplands and pastures is estimated in the range of 2.2-6.6 Gt $CO_2$-eq $yr^{-1}$,[198] as well as a small amount from biomass burning of around 0.3 Gt $CO_2$-eq $yr^{-1}$;[197] (3) $CO_2$ emissions from energy use in agricultural machinery are estimated at 1.0 Gt $CO_2$-eq $yr^{-1}$.[199] Given this, the total current estimate of all GHG emissions as a result of food production is in the range of 8.5 to 13.7 Gt $CO_2$-eq $yr^{-1}$. Total emissions from food production have been relatively stable since 1990, growing at less than 1% per year, as increases in production have been offset by decreasing emissions intensity per unit of product.[197,199]

### **Scientific target for GHG emissions from food production -** Global GHG emissions of $CH_4$ and $N_2O$ kept at or below 5 Gt $CO_2$-eq $yr^{-1}$

Determining what the maximum allowed share of the remaining global carbon budget should come from food production is complex, and any scientific target will depend on viability and costs of emission reductions in other sectors. In light of these important concerns, what we present here is a suggested global 'budget' for GHG emissions from food production by 2050 to ensure environmental sustainability. This includes only emissions of non-$CO_2$ gases ($CH_4$ and $N_2O$) and assumes $CO_2$ emissions from other sources have been reduced to zero.

We propose that global GHG emissions from food production be kept at or below 5 Gt $CO_2$-eq $yr^{-1}$ in 2050. This scientific target of 5 Gt GHG emissions from food production represent nearly half of the allowable global emissions from all sources in 2050 consistent with the RCP2.6 pathway and a 2°C temperature rise. This proportion of food production's share of global GHG emissions by 2050 is larger than today's share which roughly accounts for one quarter of total global GHG emissions.

This scientific target of 5 Gt $CO_2$-eq $yr^{-1}$ GHG emissions from food production is based on the combined $CH_4$ and $N_2O$ emissions projections of 4.7 Gt $CO_2$-eq $yr^{-1}$ from food production which is derived from runs of three integrated assessment models[200]: IMAGE 4.28, MESSAGE 4.41, and GCAM 5.30 under RCP2.6 reported in Wollenberg et al.[200] and corroborated for IMAGE by van Vuuren et al.[201] Integrated assessment models generate these results by running sub-models of climate systems, socio-economics, energy use, land use and other sub-systems, to allocate emissions reductions most cost-effectively across sectors and across GHGs. The RCP2.6 pathway projects that $CH_4$ from food production will diminish gradually throughout the 21st century whereas $N_2O$ emissions are expected to plateau after 2050.[201,202] In addition to $CH_4$ and $N_2O$ emissions, biomass burning on agricultural land, which releases $CO_2$, is expected to contribute an additional 0.7 Gt of $CO_2$ in 2050 under RCP2.6.[201,202] Combining these three gases gives a total of 5.4 Gt $CO_2$-eq $yr^{-1}$. Given the uncertainties associated with emissions estimates we set the boundary to be 5 Gt $CO_2$-eq $yr^{-1}$ with an uncertainty range of 4.7-5.4 Gt $CO_2$-eq $yr^{-1}$.

Achieving the scientific target for GHG emissions from food production is based on two fundamental assumptions. First, there will be zero $CO_2$ emissions associated with land clearance for food production. If land use change (e.g. deforestation and other land conversion) for food production is reduced to zero, then it follows that there will no longer be GHG emissions from this source. This is an ambitious goal that goes beyond the RCP2.6 pathway for $CO_2$ emissions associated with land use change. Second, there will be zero net emissions from energy use in food supply chains. Greenhouse gas emissions from fossil fuel use in food production are formally ascribed to the energy sector, not the agriculture sector, in the IPCC and other emissions-accounting frameworks. By 2050, under RCP 2.6, the energy sector is projected to have small net negative emissions of -1.2 Gt $CO_2$-eq $yr^{-1}$, due to negative emissions technologies.

More recent analyses also propose a global transition to clean energy by 2050, bringing emissions from energy use in all sectors to zero.[37]

# Freshwater use

## Overview

Food production is the world's single largest water consuming sector[1]. Agriculture consumes freshwater through rain on 84% of cropped land, and irrigation (i.e. water in freshwater lakes, rivers and aquifers) on the remaining 16%.[203] Seventy percent of all global water withdrawals are used for irrigation. This share of water withdrawals for food production varies between regions, from 21% in Europe to 82% for Africa. Overall, water consumption for food production has more than doubled between 1961 and 2000.[204]

Water functions as the bloodstream of the biosphere.[205] It underpins all biomass growth and determines the extent and distribution of biomes and ecosystems. Water drives nutrient cycles, including flushing and leaching of nutrients and pollutants (heavy metals and plastics). The hydrological cycle is strongly coupled to climate systems, including moisture feedback dynamics determining regional precipitation.[206] In this report, however, we focus on the quantity of water needed to maintain minimum environmental water flow levels in watersheds and river basins, and thus sustain ecosystem health and the benefits that society receives from these systems.

Environmental flows are the “quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems” (Brisbane Declaration[207]). They are the result of upstream freshwater partitioning of rainfall into evaporation or runoff and are also influenced by withdrawals of water for irrigation or other uses. For example, irrigated agriculture upstream, will lead to larger withdrawals of water, which in turn leads to lower environmental water flow levels in rivers. This can affect downstream ecological functions of importance for society, such as drinking water supplies, fisheries, nutrient retention, and pollution control.

To understand the effects of water withdrawals on environmental flows, it is important to distinguish between consumptive water use and non-consumptive water use. Consumptive water use refers to water that is removed from a watershed by evapotranspiration (loss of water from direct evaporation or plant transpiration), thereby directly reducing environmental water flows. Non-consumptive water use refers to water use that flows back to rivers and aquifers after use. Most irrigated water ends up as consumptive water use making it unavailable for other uses in the watershed, while a smaller part returns directly to watersheds as surface or groundwater runoff. As much as 75-84% of global consumptive water use can be attributed to agriculture.[204,208]

The minimum volume of water that needs to remain in rivers to sustain ecological functions is called environmental flow requirements (EFR). The EFR is defined as the minimum water volume, timing, and quality needed to maintain environmental function and downstream benefits. As such, EFR defines the allowable upstream withdrawals and consumption that sets the basin-scale boundaries for water use that ensures adequate environmental flows in watersheds. The hydrological dynamics (such as low-flow and high-flow values) and the ecological context of individual watersheds and river basins influence the EFR values.[209] As such, water is best analyzed regionally at the basin level.

## **Scientific target for freshwater use from food production -** Global consumptive water use kept at or below 2500 km$^3$ yr$^{-1}$

The original planetary boundary for water was proposed as 4,000 km$^3$ yr$^{-1}$ based on a global analysis not accounting for the distinct hydro-ecological contexts and EFR requirements of individual river basins.[194] This boundary did not include water use by crops in rain-fed agriculture nor water loss through evaporation from dams.[210] Some have argued that this boundary is too high, and should be lower.[211] Gerten et al.[212] refined the water boundary with a global analysis at the scale of river basins of EFR requirements quantifying available freshwater withdrawals if EFR requirements were to be respected. Gerten et al. offers a more conservative global freshwater planetary boundary of 2,800 km$^3$ yr$^{-1}$ for all human use including for food production.[212] Current consumptive water use by all human activities has been estimated to be in the range of 1800-2100 km$^3$ yr$^{-1}$, of which food production uses between 1400-1800 km$^3$ yr$^{-1}$.[204,208]

For setting a global scientific target for consumptive water use from food production, we have chosen to adopt the more conservative planetary boundary of 2,800 km$^3$ yr$^{-1}$.[212] Agriculture's current share of global consumptive water use is 75%-84%.[213] If this is maintained, food production’s share of the planetary boundary for freshwater would be 2,100-2,352 km$^3$ yr$^{-1}$. Given that food production is fundamental to human well-being and that closing yield gaps in many parts of the world is essential to feeding a global population, we suggest that the agricultural sector should be allowed a larger future allocation of the overall planetary boundary. Setting the agricultural share of the 2800 km$^3$ yr$^{-1}$ planetary boundary to 90% by 2050, rather than the current 75-84%, yields a global water boundary for food production of approximately 2,500 km$^3$ yr$^{-1}$. However, recognizing the uncertainty in these estimates, we have adopted Gerten et al.[212] uncertainty range of 1100-4500 km$^3$ yr$^{-1}$ and applying a 90% allocation for food production gives us an uncertainty range rounded to 1000-4000 km$^3$ yr$^{-1}$.

We believe increasing food production’s share of the global consumptive water use to 90% is feasible given that many technological solutions currently exist to limit consumptive water use in industry and domestic sectors. Wada et al.[204] find that consumptive water losses in industry are 20% of water withdrawals in high income countries with better technologies, but 35% in middle-income countries and 60% in low income countries. This suggests that significant reductions are possible through greater adoption and use of existing technologies. In food production, consumptive water use is unavoidable since plants transpire to grow and it is very difficult to have zero net evaporation over soil. Management practices can reduce evaporative losses through better irrigation technologies, however some losses will remain unavoidable simply due to plant growth.

## Regional Considerations

The global estimate of consumptive water use masks significant regional variations, with some regions well within the boundary and others facing severe water shortages. These are particularly true in arid regions which are chronically short of water and where basin scale EFR are systematically overtaken by irrigation. These regions include specifically West Asia and North Africa, parts of the Andean region in South America, portions of the West Coast of the US, the Indo-Gangetic plains and the Yang-Tse basin (Figure 5). This highlights the fact that water use is an issue at the regional and river-basin level and local and regional boundaries need to be set depending on their specific EFRs. The global boundary proposed here is an aggregate of water use by region. In addition to using EFRs as local and regional level boundaries, Gleick and Palaniappan (2010) propose using peak nonrenewable water and peak ecological water, where the total costs of ecological disruptions from water use exceed the total value provided by humans, as indicators of freshwater withdrawal and use.

Models of global water use indicate that up to 87 countries (depending on the population scenario) will likely exceed their EFR by 2050; up from 66 countries in 2000. Thirty of these countries are required to import food because of water limitations to local food production.[214] These countries are mainly located in North Africa and the Arabian Peninsula where irrigation is the main source of freshwater. Over-consumption of freshwater is most acute in low-income countries or in densely populated less industrialized nations.[212]

There will be an increasing need for trade in water-intensive products (virtual water) to the world's water limited basins to maintain extraction below EFRs. Assuming an ideal trade scenario, the integrity of specific water basins could be maintained through trade. Surplus basins around the world could deliver water to deficit basins by trading water-intensive food products (Panel 11). This would require unimpeded food trade and all countries to possess sufficient foreign currency to purchase food. In the current political climate, however, there is high pressure towards enhancing food sovereignty (or self-reliance) through local food production. This places tremendous pressure on water resources especially in arid and semi-arid developing countries. Low-income nations that are unable to trade because of political or economic reasons are most at risk.

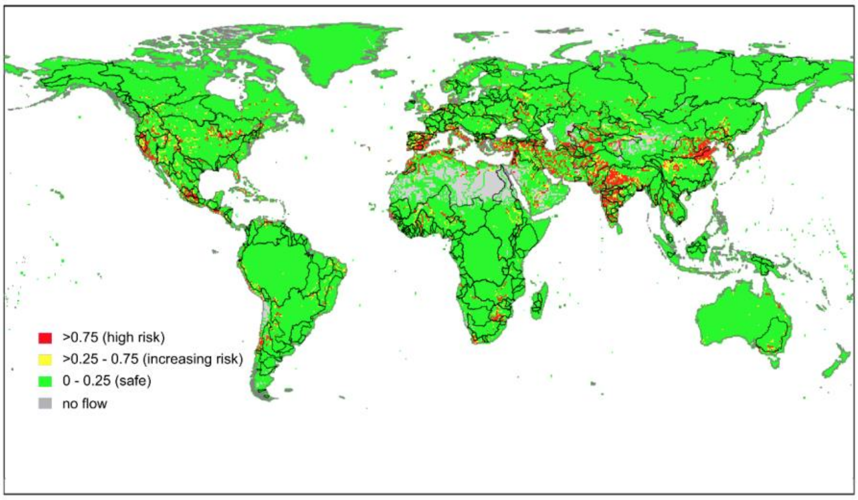


**Figure 5.** Transgression of the allowed monthly water withdrawals as % of mean monthly river flow (fraction of maximum allowed level) during months that show such an exceedance[190]. For example, green (within planetary boundary for water use) means that average exceedance in the respective months is still below the uncertainty range (Source: Steffen et al.[190])

There is good evidence, however, that increases in water productivity (more crop per drop) of 20% are possible and could help to alleviate water stress in many regions of the world. De Marsily and Abarca-del-Rio[215] review numerous sources and find this value within reach, especially when done with increases in crop yield, which in turn results in an increase in water productivity.[216,217] These values confirm the findings of Cai and Rosegrant[218] who estimated increases in water productivity of 33% for rice and up to 50% for cereals by 2025 resulting from improvements in crop yields and water-use efficiency. Similarly, Jägermeyr et al[219] estimated that improvements in crop water productivity of 9-15% are possible by replacing surface irrigation systems with sprinkler and drip systems, and significantly larger improvements can be achieved in the Indus river basin and other low efficiency irrigation zones.

# Nitrogen and phosphorus flows

## Overview

Nitrogen (N) and phosphorus (P) are nutrient elements, vital to both structure and metabolism of living organisms on land and in the oceans. N and P are both critical to plant growth and their natural availability limits plant growth in most terrestrial ecosystems. Supply of N and P fertilizers to croplands is essential for maximizing crop yields and will continue to be necessary for feeding a growing global population.[220-223]

The production, application and trade in fertilizers plays a central role in disrupting global N and P cycles. Excessive N and P application in food production has substantial consequences, notably in runoff into streams and rivers driving the eutrophication of freshwater and marine ecosystems and subsequent development of hypoxic (oxygen-free) conditions causing fish dieback and other environmental harm.[19,224] Though mostly driven by excessive fertilizer application in food production, human sewage is also an important point source. Atmospheric N deposition, usually carried from rain, snow, or fog to the earth's surface, is a third important contaminant source, particularly in countries with high $NO_x$ (i.e. NO and $NO_2$) and $NH_3$ emission rates.[225]

In addition to eutrophication of aquatic ecosystems, nitrogen application in agriculture can have several other environmental and health impacts, including: (i) eutrophication of terrestrial ecosystems, reducing their biodiversity and altering ecosystem functions[226-228] (ii) acidification of water and soils by ammonia ($NH_3$) emissions,[229,230] (iii) nitrous oxide ($N_2O$) emissions, which is a potent greenhouse gas,[231] (iv) groundwater contamination by nitrates ($NO_3$) with negative impacts on human health,[232,233] and (v) creation by $NH_3$ of fine atmospheric particulate matter and its harm to human health[234]. Agricultural N addition also drives $NO_x$ emissions which are a major source of particulate and ozone pollution[235,236] and contribute to reduced crop yields [237,238].

Nitrogen fertilizer is created using the Haber-Bosch industrial process to convert plentiful non-reactive nitrogen gas ($N_2$) to ammonia ($NH_3$). This process is highly energy intensive and associated with substantial levels of GHG emissions. Phosphorus fertilizer, on the other hand, is a non-renewable resource that is mined from a finite number of phosphate rock deposits. At current and projected rates of exploitation, these deposits are estimated to run out within 50 to 100 years.[239]

## Nitrogen and phosphorus for people and planet

A grand challenge for humanity is to harmonize the maximum allowed N and P loading into the biosphere to maintain a stable Earth system, with the necessary amounts of N and P required to feed humanity.[240] Estimates of "human needs" show that feeding nearly 10 billion people by 2050 on current cropland will require higher annual global applications of N and P fertilisers[241] that exceed the planetary boundaries for N (62-82 Tg N $yr^{-1}$) and P (6.2-11.2 Tg P $yr^{-1}$).

However, the Earth system approach taken here, where what counts is the aggregate impact caused by food production on the biosphere, opens up significant opportunities if practices are adopted where (i) more food is produced per unit of N/P input, (ii) loss of nutrients is reduced to a minimum and, in particular, (iii) nutrients are recycled, not only on farmers' fields, but also at system level, e.g., in the rural-urban interface. Experience shows that there are ample opportunities to reduce environmental impacts of food production by eliminating nutrient overuse and run-off into aquatic systems, while still allowing an increase in food production.[242]

Closing nutrient loops and using N and P more efficiently is one opportunity for producing more food without releasing more reactive N and P into the biosphere. This includes applying the right type of fertilizer, with the right amount, at the right time, and right place. It also involves efforts to recover nutrients (i.e. recycling) in usable form from places in the food system where they concentrate, such as sewage treatment plants, food processing plants, compost operations, and livestock production facilities. Adopting a closed loop system to global food production recycles N and more importantly P within food systems, keeping it out of the biosphere and decreasing the environmental impact. Improved nutrient-use, and reuse efficiency can simultaneously permit increased global application of N and P to close yield gaps (i.e., the difference between attainable and actual yields) while reducing the total global need for new N and P fertilizer synthesis.

Another opportunity arises from the redistribution of N and P use to close yield gaps. On a global scale, N and P fertilizer application is highly unevenly distributed ranging from N and P inputs insufficient to close yield gaps to excessive surplus application in many developed and rapidly growing economies.[243] Many developed nations apply N in excess, having N application rates much higher than needed to obtain current yields. In contrast, many developing countries have yields that are only ½ to ¼ of those that could be obtained with appropriately-increased and well-timed fertilizer applications.[244,245]

## **Scientific target for nitrogen use from food production -** Global nitrogen application kept at or below 90 Tg N $yr^{-1}$

Nitrogen fluxes (net movement of N) to air and water react directly to increases in N input because N does not build up in soils. Therefore, the more N that is added to croplands the more N losses that can be expected due to leaching and runoff into aquatic systems, volatilization to the air, and crop removal, which accounts for the majority of N that leaves the soil system. This direct link between inputs and losses was the basis for the critical anthropogenic N input calculation by De Vries et al.[241], which is the amount of N that can be applied (from fixation by legumes and fertilizer) globally for food production without causing eutrophication. The critical N input (i.e. N application) is a fraction of the current global N input, which currently exceeds planetary boundaries.

The N boundary for global food production is derived by multiplying current estimated industrial (from Haber-Bosch) and biological N fixation with mean fractions varying between 0.50 and 0.67 of current global N application. These mean fractions relate to the percentage of reductions in current global N application necessary to keep N concentrations in runoff at safe levels varying between 1 and 2.5 mg N $^{-1}$.[241] Current total global N application is estimated to be approximately 130 Tg N $yr^{-1}$.[241,246,247] Multiplying 130 Tg N $yr^{-1}$ with 0.50 and 0.67 leads to a range of 65-87 Tg N $yr^{-1}$, with the proposed global N application boundary for food production set at 90 Tg N $yr^{-1}$ and an uncertainty range rounded to 65-90 Tg N $yr^{-1}$. This is slightly higher than the boundary proposed by Steffen et al. (2015) who used a total global N application of 121.5 Tg N $yr^{-1}$, which may be based on an underestimation of fertilizer use.

The proposed N boundary from food production, may still be an underestimate given that it is based on current global patterns of N use, which includes overuse in some areas and underuse in others. In deficit areas, additional N input to increase crop yield is possible without negatively impacting the environment. In addition, the N boundary does not consider efficiency gains through closing N loops. If global redistribution of N and closing N loops are both considered, a higher global use of N might be possible without exceeding the N boundary for food production. We therefore include an upper uncertainty range of 90-130 Tg N $yr^{-1}$ that considers an increase in N fertilizer[244] use if global redistribution of N and closing N loops are adopted. This upper value of 130 Tg N $yr^{-1}$ is a “human needs” estimate for the amount of N that may be needed to feed a global population of nearly 10 billion people.

## **Scientific target for phosphorus use from food production -** Global phosphorus application kept at or below 8 Tg P $yr^{-1}$

The planetary boundary of 6.2 Tg P $yr^{-1}$ (6.2-11.2 Tg P $yr^{-1}$), originally proposed by Carpenter and Bennett[248] and adopted by Steffen et al.[190] was a regional-level and short-term boundary to avert widespread eutrophication in regional watersheds. This boundary applied primarily to global croplands given that most P addition to watersheds is from fertilizer use. This boundary is based on the total global flow of P in erodible soil to freshwater systems minus current weathering rates. A criticism of this approach is that it assumes that soil erosion is the principal source of P to freshwater systems. Phosphorus that is moved off the field in crops, consumed by animals and humans, and subsequently excreted as manure and human waste and ending up as P inputs to freshwater systems are excluded. Therefore, this may drive an overestimate of the long-term global P boundary of sustained flow of 11 Tg P $yr^{-1}$ (11-100 Tg P $yr^{-1}$) from freshwater systems into the ocean.

De Vries[249] developed a global phosphorus-flow model for food production that takes into account some of the criticisms of the original approach used by Carpenter and Bennett[248] but did not factor in other fluxes such as weathering rates. In it, the external acceptable global P input from food production to the biosphere is determined by the long term (thousands of years) acceptable accumulation of P in soil and sediments and inputs to surface water (oceans) due to runoff and leaching that leave P concentration equal to a critical threshold for eutrophication. The boundary is affected by uptake and excretion of P by humans to freshwater systems (stored in sediments) and recycling of human waste to soils (stored in soils). It assumes full P recycling of animal manure. Using this approach and assuming no human waste recycling leads to a long-term P global input range from food production of approximately 6-12 Tg P $yr^{-1}$. This new calculation is similar to the Carpenter and Bennett[248] input range. Given this, we propose the global long-term P application boundary from food production to be 8 Tg P $yr^{-1}$ with an uncertainty range of 6-12 Tg P $yr^{-1}$.

This P boundary may also be an underestimate given that it does not consider the critical impact of improving P use efficiency through closing P loops through recycling and reducing point source P loads. It also does not consider global redistribution of P use from over-applying to under-applying regions. This is important because unlike nitrogen, P is adsorbed into the soil and can build up and be held in soil P stocks. Increasing soil organic matter and carbon stored in soils increases the capacity of soils to store P. Phosphorus leaching and runoff to surface waters occurs when P stocks in soils are saturated and P input as fertilizer is greater than the amount of P removed during cultivation and harvest. When soils are P deficient (i.e. stocks are not saturated) additional inputs of P are possible and will increase yields with minimal environmental harm. Together, these considerations effectively increase the P boundary.

Currently, global P stocks are deficient in some areas, while saturated in others. To increase crop yields, global phosphorus stocks should be saturated globally, and P application should maintain P saturation by replacing P that is removed during cultivation and harvest. Doing this would close yield gaps which is necessary for feeding nearly 10 billion by 2050. We estimate that this can be accomplished through short term time-bound (over a few years) global P application of 16 Tg P $yr^{-1}$ targeting P deficit soils and therefore propose an upper input range of 8-16 Tg P $yr^{-1}$, while maintaining a P boundary of 8 Tg P $yr^{-1}$. This can be achieved by recycling 50% of human waste and reapplying the recycled P to croplands. This will become even more important as the global population increases by over 2 billion people by 2050.

# Biodiversity loss

## Overview

Food production is particularly dependent on biodiversity, and inversely, biodiversity conservation is fully dependent on food production. The diversity and richness of all living organisms on land and in water, ranging from animals, trees, plants to micro-organisms and phytoplankton, is necessary for the health and stability of ecosystems[250-252] and in turn for the productivity and resilience of food production systems. This functional value of biodiversity is often poorly understood and radically undervalued.[253-256] Biodiversity generates critical ecosystem services necessary for human well-being that include support to food production, pollination, pest control, heat regulation, carbon sinks, and moisture feedback for rainfall amongst others. The nutritional quality, protective attributes, and flavors of most plant foods is itself a function of evolutionary interactions between species.[257]

Despite this, the fundamental role of biodiversity in the productivity and resilience of food production is colliding with the observational evidence that we have entered the 6th mass species extinction on Earth, losing species at a rate 100 - 1000 times greater than background Holocene rates.[258-260] Biodiversity is decreasing at an alarming rate, as measured through rates of species extinction [259,260], local changes in community composition, declines in population abundance [259] and reduced biodiversity intactness[193]. This loss of biodiversity, including agricultural biodiversity (Panel 7), is an increasing threat to the Earth system,[250,252] and global food security and has the potential to fundamentally undermine our ability to sustainably feed a global population of nearly 10 billion people by mid-century.

**#### Insert Panel 7 – Agricultural biodiversity ####**

## Food production as a driver of biodiversity loss

Multiple human actions contribute to biodiversity loss. Terrestrial and aquatic habitat loss, habitat fragmentation, climate change, chemical pollution, invasive species and unsustainable harvest of wild species have been identified as primary drivers.[254,261] However, habitat loss and fragmentation, particularly through the human appropriation of land for food production, is the single greatest current driver of biodiversity loss.[254,262] Based on the IUCN classification of bird and mammal extinction risks, 80% of the mammal and bird species that are threatened with extinction have agriculture as a cause of those threats (Figure 6).

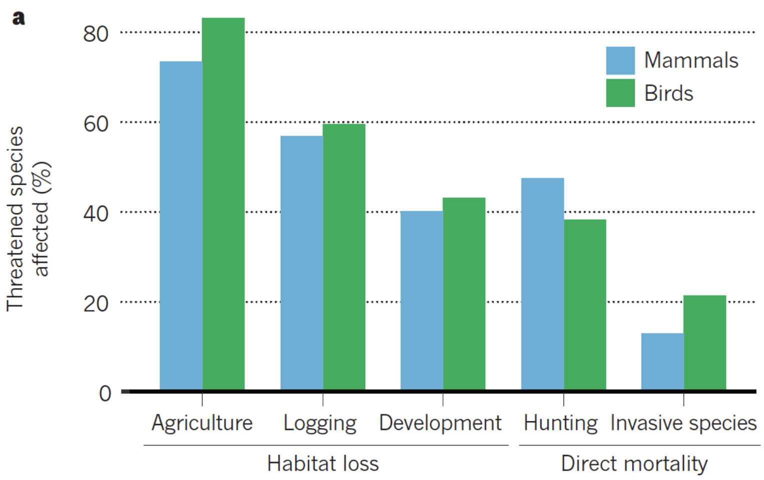


**Figure 6.** Relative impact of agriculture and other activities on mammals and bird species threatened with extinction based on IUCN extinction risks. Source: Tilman et al.[263]

Increasing crop yields is often cited as a method for halting or limiting land expansion for agriculture and its detrimental impact on biodiversity. However, increasing crop yields has often led to excessive fertilizer and pesticide applications, and inefficient irrigation which have significant detrimental effects on local biodiversity loss through their impact on terrestrial and aquatic systems, notably contamination by excess nutrients, and reduced environmental flows in aquatic systems as discussed in the previous section. Taken together, expansion and to a lesser extent excessive (unsustainable) intensification of agriculture are key drivers of biodiversity loss.[264]

## **Scientific target for biodiversity loss from food production -** Global biodiversity loss kept at or below 10 E/MSY

Current extinction rates[265] and population declines[259] are orders in magnitude higher than Holocene background rates of approximately 1 extinction per million species per year (E/MSY). It is unknown how many species can be lost while still maintaining our ability to feed humanity, but each additional species lost represents a fundamental reduction in resilience and capacity to respond to environmental change.[266] A precursor to extinction is the reduction of species' population sizes and local extinctions. For example the loss of 75% of insect biomass[267] over 30 years and 30% of farmland birds over 15 years, as noted in recent European studies, occur long before global extinctions and severely impact biodiversity's capacity to support food production, gene flow and other ecosystem services.

A background extinction rate of 1 E/MSY across many taxa has been proposed as a benchmark against which to assess the impacts of human actions.[260] There is a high degree of uncertainty over what level of higher-than-background extinctions the Earth system can tolerate, which is distinct from, and less conservative than intrinsic biodiversity value benchmarks which argue for zero species loss. This uncertainty therefore justifies both a high uncertainty range and our proposed scientific target of <10 E/MSY, which is within one order of magnitude greater than the background extinction rate and the same as put forth by Steffen et al.[190] However, given that we do not know what levels of, or types of, biodiversity loss may possibly trigger irreversible changes to the Earth system, the boundary from food production, in principle, should be set at a rate of loss no greater than the historical background rate. We suggest, therefore, an uncertainty range of 1-80 E/MSY, with the lower value being equal to the background extinction rate and the upper value being agriculture's share of impact on species decline (80%) of the upper value of the uncertainty range (100 E/MSY) proposed by Steffen et al.[190]

While E/MSY is a logical metric for measuring biodiversity loss, several caveats are important to recognize. First, E/MSY is typically measured on geological timescales rather than on the much shorter ecological time scales of global environmental conventions including the Convention on Biological Diversity (CBD). However, given that early indications of global extinctions are becoming observable in ecological timescales is cause for significant concern requiring urgent action. Second, regional reductions in species populations [259] and local extinctions both serve as a precursor to global extinction. These are better suited for indicating potential loss of global biodiversity and concomitant ecosystem services[259] and can be measured using biodiversity intactness. Third, not all species have the same measurable impact on Earth system processes, and thus species loss may not capture the extent to which an individual species lost affects global processes[268]. Despite these limitations, models based on well-documented species area relationships (SAR) have recently been used to extrapolate the extent to which anticipated land conversion could contribute to species loss.[269-271] As such, we maintain E/MSY as the appropriate metric for measuring global biodiversity loss from food production, but suggest measures of biodiversity intactness and Half Earth as strategies to guide action.

# Land-system change

## Overview

Globally, the total net area devoted to food has remained relatively constant since the mid-20$^{th}$ century. This masks the real picture, however, as substantial reductions in agricultural land have occurred in the temperate regions of Europe, Russia and North America, while substantial agricultural land expansion has occurred in the biodiversity rich tropics. Food production is currently the largest driver of land-use and land-use change, mainly through the clearing of forests and burning of biomass. Between 2000 to

2014, Brazil lost on average 2.7 million hectares (ha) of forest per year, the Democratic Republic of Congo on average 0.57 million ha per year with a 2.5 factor increase since 2011, and Indonesia lost on average 1.3 million ha per year with 40% occurring in primary forest.[272] This land-system change is a major contributor to biodiversity loss and GHG emissions (see section on GHG emissions) and undermines the other biophysical processes that regulate the state of the Earth system.

To maintain a stable Earth system in the Anthropocene, the land use challenge is to safeguard critical terrestrial and marine biomes that regulate the state of the planet and provide ecological functions that support food production. The original control variable for land-system change in Rockström et al. 2009 was cropland use, i.e., the maximum allowed conversion of natural terrestrial ecosystems into cropland to safeguard critical biomes. This was set at no more than 15% of global ice-free land surface, of which approximately 12% was under cultivation a decade ago[273] and which allowed for approximately 3% expansion. The updated control variable in Steffen et al.[190] was shifted to a more direct estimate of the minimum extent required to safeguard critical biomes as intact ecosystems.

Currently, approximately 51% of the global land surface can be classified as intact ecosystems with a Biodiversity Intactness Index (BII) of >90.[193,274]. BII provides a measure of the intactness of the local communities within a region relative to their original state. However, intact ecosystems vary globally with more intact biomes in boreal and tundra biomes (see Figure 7).[274] Of this 51%, approximately 15% of global land area has legal protection status and can be classified as natural habitats which are home to unique species, many that are severely threatened and require large intact areas with little to no human intervention. The CBD's Aichi Target 11 has set 17% as the area-based global target for protected areas, with a focus on the legal protection of Key Biodiversity Areas[275], and Hotspots.[276]

The remaining 36% of intact ecosystems do not have legal protection status but maintain high biodiversity intactness values.[274] The boreal and tundra biomes are more than 70% intact, contrasted with the Mediterranean biome, which is less than 17% intact[274]. The most threatened biomes are those with the greatest agricultural value, including grassland, dry tropical forest, and temperate forest biomes. In contrast, biomes that have lower value for food production are well conserved and protected, notably the higher latitude tundra and boreal biomes. The combination of intact biome area, with a target of >50%, and biodiversity intactness, with a target of >90, provide a powerful combination of metrics speaking to the degree to which progress must be made to protect global biodiversity (Figure 7). Because biodiversity is local, and non-tradable (e.g. orangutans are unique to Indonesian forests, gorillas to Central African forests and prehensile tailed monkeys to neotropical forests), these targets must be set at the ecoregion level thus ensuring an even distribution of conservation efforts globally and avoiding targeting conservation efforts on low value regions while sacrificing high conservation value areas.

Croplands and grazing lands (i.e. rangelands and pasturelands) occupy approximately 40% of ice-free terrestrial landmass. Jointly, these agricultural systems are the world's largest ecosystems and in addition to food production, they provide other important services such as habitat for biodiversity and carbon sinks. Griscom et al.[277] showed that between 2 to 8 Gt $CO_2$ can be sequestered by using practices such as nutrient management, trees in croplands, improved paddy rice production, and grazing animal management.[277]

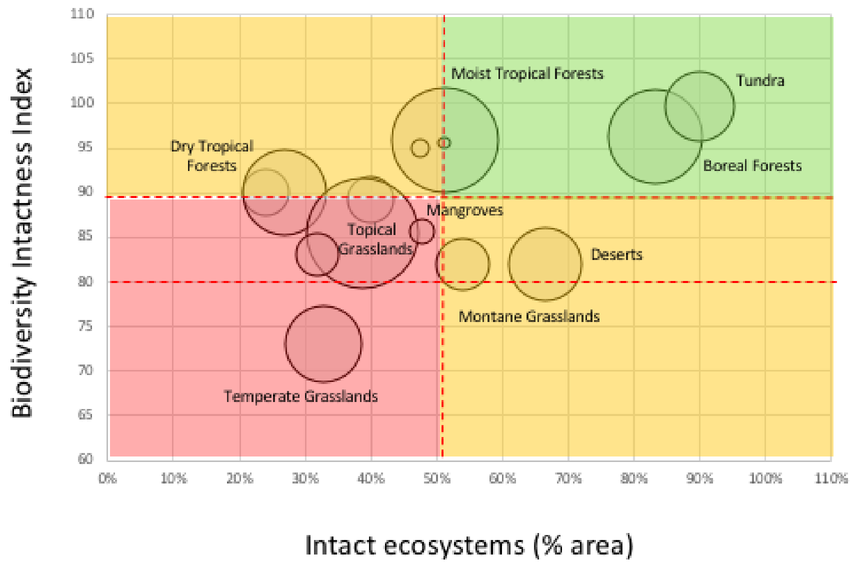


**Figure 7.** The relationship between two metrics for measuring biodiversity loss and land-system change: (x-axis) area-based intactness and Half Earth strategy proposed by Wilson (2016) and Dinerstein et al. (2017); and (y-axis) the species composition-based biodiversity intactness index (BII) proposed by Steffen et al. (2015) and analyzed globally by Newbold et al. (2016). Four biomes (green shaded area) have both a BII>90 and more than 50% by area intact while four biomes (red shaded area) have neither. The remaining six biomes are below one, but not both targets (yellow). The size of the circles reflects the area of the biome in question.

Grazing and pasture lands occupy approximately 23% of total ice-free land surface and are important for biodiversity conservation and carbon sequestration. They may also be particularly important in restoration strategies in formerly grassland biomes or reforestation in formerly forest biomes, which will be necessary for removing massive amounts of $CO_2$ from the atmosphere to stay well below 2°C. Reforestation, however, is constrained by land availability and therefore reforestation of degraded pastures and rangelands in original forest biomes offers an opportunity to remove $CO_2$ from the atmosphere while providing additional biodiversity conservation benefits.[277] Conversion of the remaining rangelands and pasturelands should be treated with caution given the potentially high opportunity cost resulting from biodiversity loss and $CO_2$ emissions.

## **Scientific target for land-system change from food production -** Global cropland use kept at or below current levels of 13 M km$^2$

We use minimum forest cover, BII, and area based intactness for key biomes as guides for setting the scientific target for land use from food production.[190] Given that agriculture is the largest driver of deforestation and land-use globally, the only way to achieve the Paris Agreement and reduce biodiversity loss is to halt agricultural expansion into forest areas and other natural ecosystems. This means keeping global land use from food production at or below current levels of 13 M km$^2$ (11-15 M km$^2$).

The scientific target for food production set here defined in the context of the major global pressures posed by producing food at a time when humanity has already transformed more than 40% of all terrestrial ecosystems for food production. Recent proposals suggest that we can halt biodiversity loss and conserve at least 80% of preindustrial species richness by protecting the remaining 50% of Earth as intact ecosystems.[274,278] This suggests that the quantitative boundary estimates for land-system change and biodiversity loss proposed by this Commission can be translated to (globally) *zero* future land conversion of natural ecosystems into farmland, i.e., to adopt a "Half Earth" strategy. This strategy is in line with the biome or regional boundary proposed by Steffen et al. (2015) of maintaining a biodiversity intactness index (BII) of 90% (see Figure 7). Adopting a Half Earth strategy, if implemented by biome, would have multiple co-benefits such as maintaining functional diversity in ecosystems, reducing GHG emissions from agriculture, forestry, and other land use (AFOLU), and stimulating afforestation or reforestation efforts which are important for helping to meet the Paris Agreement (see Panel 6). The Half Earth strategy recognizes that humanity has now reached the end of its >8,000-year era of expanding agricultural area on Earth.[190,278] Half Earth can be achieved either through legal protection or through biodiversity compatible land uses such as sustainable harvest of native forests, indigenous areas, or low intensity grazing systems in grassland ecosystems or other land uses that maintain BII>90.

Staying within the biodiversity boundary for food production also depends on fine scale conservation efforts within agricultural landscapes. Most of biodiversity loss is driven by habitat fragmentation and agricultural intensification including the loss of fallows, buffer systems, and embedded conservation structures in agriculture. Integrating at minimum 10% ecologically conserved land at very fine scales (<1 $km^2$) into agricultural systems allows for habitat connectivity, which is essential for species survival, and access to the services biodiversity provides to support food production. In addition, climate change driven alteration of ecosystems is second to land use change in terms of threats to biodiversity loss. Ensuring that species ranges can shift on pace with climate change requires conservation action both on habitat and connectivity.[279,280]

Maintaining at least 10% ecological conservation within agricultural landscapes yields additional benefits. This includes pollination services, of which more than 75% of staple crops are dependent and contribute to 35% of global crop production by volume for fruits, nuts, vegetables and other species essential to healthy diets. Meta-analyses of pollination and pest control services in agriculture document that species providing these services rarely move more than 100’s of meters from conservation infrastructure.[281] Natural vegetation along streams (riparian buffers) and conserved field margins can intercept up to 90% of excess nutrient run-off during normal flow events,[282] which is another co-benefit of this conservation strategy. Lastly, conservation within croplands and rangelands has the potential of increasing carbon sequestration potential.

## Scientific targets and strategic directions for sustainable food production

Table 3 provides scientific targets for the planetary boundaries for food production presented in this Commission. These global scientific targets provide an integrated definition of sustainable food production in the Anthropocene, which furthermore can be translated to science-based targets for different scales (regions, nations) and sectors. Furthermore, the scientific targets for sustainable food production presented here (Table 3), can be translated to strategic directions including:

- Feed humanity essentially on current agricultural land, which means a transition to *zero* expansion of new agricultural land at the expense of natural ecosystems.
- Urgent and radical move towards halting loss of biodiversity, which essentially translates to *zero* loss of biodiversity.
- Decarbonise the entire food value chain from production to consumption, i.e., *zero* fossil-fuels by 2050, and maintain GHG emissions at or below 5 Gt $CO_2$-eq $yr^{-1}$ for the biologically driven greenhouse gases ($CH_4$ and $N_2O$) associated with food production.
- Radical improvement in systems scale (rural-urban) nutrient use efficiency and recycling of N and P.
- Reduce food loss and waste by 50% to decrease pressure on food demand.
- Transform to sustainable intensification of food production, adopting sustainable practices for soil, water, nutrients and chemicals, corresponding to nothing less than a new agricultural revolution.
- Integrate 10% ecological conservation into current agricultural landscapes and regenerate and reforest degraded land.
- Adopt a "Half Earth" strategy for biodiversity conservation by protecting 50% of Earth as intact ecosystems.

**Table 3.** Scientific targets for six key Earth system processes and the control variables used to quantify the boundaries.

| Earth system process | Control variable | Boundary | Uncertainty Range |
|---|---|---|---|
| Climate change | GHG ($CH_4$ and $N_2O$) emissions | 5 Gt $CO_2$-eq $yr^{-1}$ | (4.7-5.4 Gt $CO_2$-eq $yr^{-1}$) |
| Nitrogen cycling | N application | 90 Tg N $yr^{-1}$ | (65-90 Tg N $yr^{-1}$*)<br>(90-130 Tg N $yr^{-1}$**) |
| Phosphorus cycling | P application | 8 Tg P $yr^{-1}$ | (6-12 Tg P $yr^{-1}$*)<br>(8-16 Tg P $yr^{-1}$**) |
| Freshwater use | Consumptive water use | 2,500 $km^3$ $y^{-1}$ | (1000-4000 $km^3$ $yr^{-1}$) |
| Biodiversity loss | Extinction rate | 10 E/MSY | (1-80 E/MSY) |
| Land-system change | Cropland use | 13 M $km^2$ | (11-15 M $km^2$) |

* Lower boundary range if improved production practices and redistribution are not adopted
** Upper boundary range if improved production practices and redistribution are adopted and 50% of applied P is recycled

## An Earth system approach to assessing sustainable food production

A reliance on using only one or a few indicators of environmental sustainability, as is common in many studies, is a limitation from an Earth system perspective because the metrics used influence the conclusions that can be drawn. For example, if only GHG emissions is assessed then it might be inferred that a single intervention such as a dietary shift would be sufficient for ensuring environmental sustainability when in fact other key biophysical processes such as water use, land-use, nitrogen and phosphorous cycling and biodiversity loss might still exceed food production boundaries.

Using an Earth system approach to define sustainable food production necessitates that we broaden our view of environmental sustainability to include all of the biophysical processes described in this report. This wider perspective allows us to better assess which combination of interventions are necessary for staying within all of the planetary boundaries for food production while still delivering healthy diets to a global population. Achieving this “win-win” dietary pattern, which is both healthy and environmentally sustainable, is a prerequisite for meeting the SDGs and Paris Agreement.

Looking forward toward the SDG timeline to 2030 and Paris Agreement timeline to 2050, means reconciling the fact that the global population will increase to nearly 10 billion people. Meeting the demands of a global population by 2050 necessitates that we find solutions to the dilemma of increasing food production while decreasing environmental impact. Given this, we not only need to understand the link between diets and environmental sustainability, we also need to understand the linkages between other interventions such as food production practices and food waste and their impact on environmental degradation. This is important because the environmental impacts of certain foods are highly dependent upon production practices.

# Chapter 4 - Achieving healthy diets from sustainable food systems

## Environmental impacts of individual foods and dietary patterns

A large body of literature has examined the impacts of foods and dietary patterns on the environment, with most assessing the impact of GHG emissions. For example, a recent systematic review by Clune et al.[283] presents the GHG emissions of different food categories from LCA studies and shows a clear hierarchy of emissions whereby grains, fruits and vegetables have the lowest impact and meat from ruminants the highest impact. A few others have looked at water use.[284] Overall, studies concur that plant-based foods have a lower environmental impact per unit weight, per serving, per unit of energy, or per protein weight than animal source foods across a range of environmental indicators (Figure 8).

Environmental impacts of foods can be measured using various units including per kcal, per g protein, or per serving, depending on the nutritional contribution of each food.[4] Using a universal indicator to measure environmental impact can be misleading for certain foods. For example, vegetables contain very few calories per serving and using kcal to measure their environmental impact would indicate that some vegetables would have relatively high environmental footprints when in fact from a per serving basis their environmental impacts are low. Given this, environmental impacts are shown per serving in Figure 8.

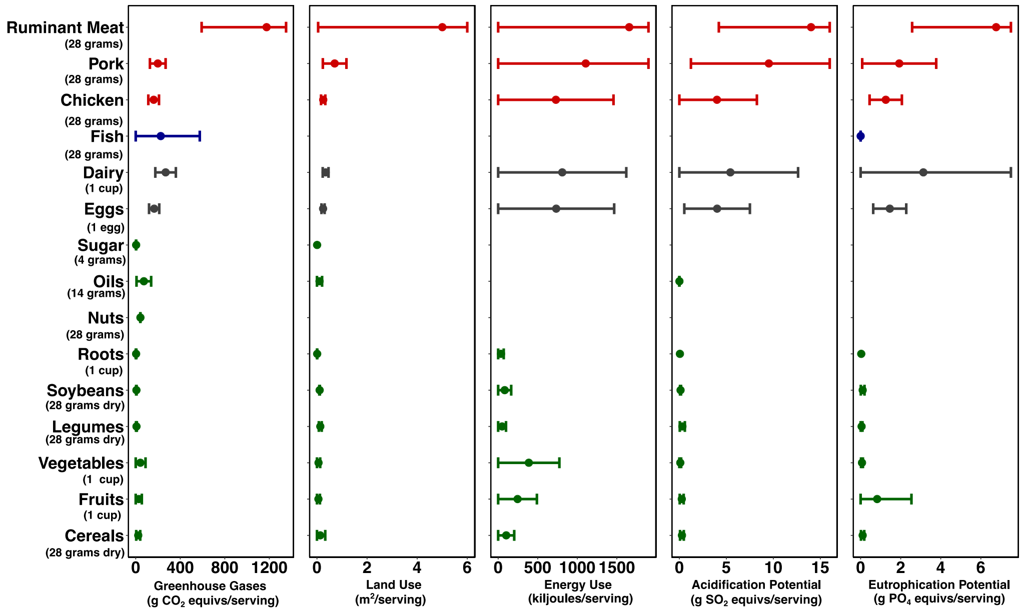


**Figure 8**. Environmental impacts per serving of food produced. Bars show means +/- one standard deviation. Plant-based foods are colored in green; fish in blue; dairy and eggs in grey; and meats in red. Data sources are Tilman and Clark (2017) and Clune et al (2017).[41]

## Environmental impacts of the food system

Devising a sustainable food system that can deliver healthy diets for a growing population presents us with formidable challenges. A large body of work has emerged on the environmental impacts of various diets, with most studies finding decreasing impacts with increased replacement of animal source with plant-based foods.[4,5,285-287] Vegan and vegetarian diets were associated with the greatest reductions in GHG emissions and land use[4,288] and vegetarian diets with the greatest reductions in water use.[286] Diets that replaced ruminants with other alternatives, such as fish, poultry and pork, also show reduced environmental impacts, but less so than plant-based alternatives.[287] Overall, this literature indicates a diet that includes more plant-based foods, and fewer animal source foods would confer significant health and environmental benefits. Agricultural studies, on the other hand, have investigated potential changes in technologies and management that could decrease environmental impacts, e.g. by increasing yields on existing croplands and improving water and fertilizer management.[244,289,290]

Here we analyse what combinations of measures are needed to stay within all of the food production boundaries (Table 3) while still delivering healthy diets (Table 1). For that purpose, we use a global food systems model with country-level detail that converts consumption patterns, such as the healthy reference diet described in Chapter 2, into the associated food production needs. The model takes into account current and future projections of food demand, trade, livestock feed requirements, processing of oilseeds and sugar crops, and non-food demands for agricultural products by industry. A full description of the model is provided in the methods appendix and by Springmann and colleagues.[291] Here we extend the analysis by considering a broader set of dietary scenarios and sensitivity analyses.

For assessing the environmental impacts of food consumption we paired the model's future food projections with country-level environmental footprints which we obtained from various sources (See Supplementary Table 5).[292-295] In line with current literature[41], our results indicate that animal source foods have relatively high footprints per serving for GHG emissions, cropland use, water use and N and P application. The total environmental impacts are determined by combining region-specific footprints with estimates of food demand.

Future food demand is influenced by changes in population and income. The former changes the absolute quantity of food produced, and the latter the types of foods that are produced. With increasing income, diets are expected to shift towards high-value foods, such as meat and dairy, as well as fruits and vegetables.[296] Our baseline (business-as-usual, BAU) projections follows a middle-of-the-road socio-economic development pathway (SSP2 – see Supplementary Table 1), in which the global population is projected to grow by a third and income is projected to triple.[292]

For the BAU scenario, we project the potential impacts of food production on GHG emissions, cropland use, freshwater use, and N and P application, forecasting that these could increase by 50-90% from 2010 to 2050 in absence of dedicated mitigation measures.[291] This would push key biophysical processes that regulate the state of the Earth system well beyond the boundaries and safe operating space for food production (Figure 9). Different food groups contribute to different degrees to the environmental impacts. Animal-source foods are responsible for about three quarters of the climate change impacts, whereas staple crops, such as wheat, rice and other cereals, are responsible for a third to half of the pressures on the other environmental domains.

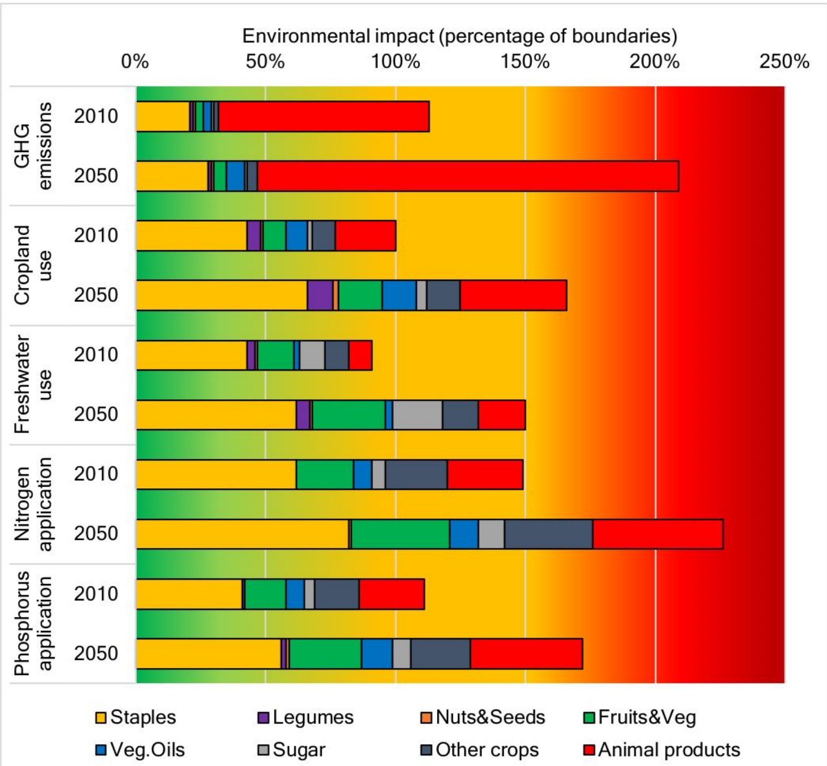


**Figure 9.** Current and future environmental impact by food groups on various Earth systems and assuming trends in consumption and production follow a business-as-usual trajectory.

## Scenarios for achieving healthy diets from sustainable food systems

Several measures exist to reduce the environmental impacts of food production. For the purpose of our analysis, we grouped them under three categories: dietary changes towards healthier diets; technological and management-related changes in food production; and reductions in food loss and waste that involves both technical changes (related to food loss during production) and behavioural changes (related to food waste at the point of consumption). The measures we considered (Table 4) have been put forward in the research literature and some have been declared as global or national goals (e.g., reductions in food loss and waste). In general, we focused on those measures that are feasible with current technologies but have not been widely adopted.

**Table 4.** Measures considered for reducing environmental impacts from food production.

| Measures | Assumptions |
|---|---|
| Dietary shift *(reference, vegetarian, vegan*, *pescetarian*) | **Reference** – As outlined in Table 1 (Ref diet Chapter 2)<br>**Vegetarian** – Meat-based protein sources replaced by a mix of plant-based proteins and fruits and vegetables; eggs and dairy consumed<br>**Vegan** – All animal-based protein sources replaced by a mix of plant-based proteins and fruits and vegetables; no eggs and dairy consumed<br>**Pescetarian** – Meat-based protein sources replaced by a mix of seafood and fruits and vegetables; eggs and dairy consumed |
| Improved production practice (*PROD*) | Standard level of ambition for improved food production practices including closing of yield gaps between attained and attainable yields to about 75%;[244,292] rebalancing nitrogen and phosphorus fertilizer application between over and under-applying regions;[244] improving water management, including increasing basin efficiency, storage capacity, and better utilization of rainwater;[292] and implementation of agricultural mitigation options that are economic at the projected social cost of carbon in 2050,[297] including changes in irrigation, cropping and fertilization that reduce methane and nitrous oxide emissions for rice and other crops, as well as changes in manure management, feed conversion and feed additives that reduce enteric fermentation in livestock.[298] |
| (PROD+) | High level of ambition for improved food production practices on top of PROD scenario, including additional increases in agricultural yields that close yield gaps to 90%;[244] a 30% increase in nitrogen use efficiency,[299] and 50% recycling rates of phosphorus;[300] phase-out of first-generation biofuels, and implementation of all available bottom-up options for mitigating food-related GHG emissions.[298] |
| Reduced food waste & loss (*halve waste*) | Food losses and waste reduced by half, in line with SDG target 12.3. |

Our analysis shows that to stay within the safe operating space for food systems requires a combination of production and dietary and management-related measures (Table 5). While some individual measures are enough to stay within specific boundaries, no single intervention is enough to stay below all boundaries simultaneously. In reference to Table 5, we discuss each boundary in turn.

**Table 5.** Various scenarios demonstrating the environmental impacts of implementing the measures outlined above. The colours illustrate whether environmental impacts transgress food production boundaries: green - below lower range value; light green - below or equal to boundary but above lower range value; orange - above boundary but below upper range value; red – above upper range value.

| Production (2050) | Waste (2050) | Diet (2050) | GHG emissions ($GtCO_2$-eq $yr^{-1}$) | Cropland use (M $km^2$) | Water use (M $km^3$) | N application (Tg N) | P application (Tg P) | Biodiversity loss (E/MSY) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Food Production Boundary | | | 5.0 (4.7-5.4) | 13 (11.0-15.0) | 2.5 (1.0-4.0) | 90 (65.0-140.0) | 8 (6.0-16.0) | 10 (1-80) | | | |
| | | | | | | | | OPTM | MAN | OPTN | NAT |
| Baseline in 2010 | | | 5.2 | 12.6 | 1.8 | 131.8 | 17.9 | 100 | | | |
| BAU | full waste | BAU | 9.8 | 21.1 | 3.0 | 199.5 | 27.5 | 2 | 36 | 153 | 1067 |
| BAU | full waste | reference | 5.0 | 21.1 | 3.0 | 191.4 | 25.5 | 2 | 45 | 120 | 1309 |
| BAU | full waste | pescatarian | 3.2 | 20.6 | 3.0 | 189.7 | 25.3 | 2 | 46 | 118 | 1313 |
| BAU | full waste | vegetarian | 3.2 | 20.8 | 3.1 | 186.9 | 24.7 | 2 | 48 | 122 | 1374 |
| BAU | full waste | vegan | 2.1 | 20.7 | 3.3 | 184.1 | 24.4 | 2 | 50 | 128 | 1431 |
| BAU | halve waste | BAU | 9.2 | 18.2 | 2.6 | 171.0 | 23.2 | 1 | 24 | 105 | 716 |
| BAU | halve waste | reference | 4.5 | 18.1 | 2.6 | 162.6 | 21.2 | 2 | 32 | 81 | 940 |
| BAU | halve waste | pescatarian | 2.7 | 17.6 | 2.6 | 160.0 | 20.8 | 2 | 33 | 78 | 940 |
| BAU | halve waste | vegetarian | 2.7 | 17.8 | 2.7 | 158.5 | 20.5 | 2 | 35 | 83 | 1000 |
| BAU | halve waste | vegan | 1.7 | 17.7 | 2.8 | 155.0 | 20.0 | 2 | 36 | 90 | 1051 |
| PROD | full waste | BAU | 8.9 | 14.8 | 2.2 | 187.3 | 25.5 | 1 | 7 | 68 | 237 |
| PROD | full waste | reference | 4.5 | 14.8 | 2.2 | 179.5 | 24.1 | 1 | 14 | 54 | 414 |
| PROD | full waste | pescatarian | 2.9 | 14.6 | 2.2 | 178.2 | 24.0 | 1 | 15 | 54 | 426 |
| PROD | full waste | vegetarian | 2.9 | 14.6 | 2.2 | 175.5 | 23.6 | 1 | 15 | 56 | 462 |
| PROD | full waste | vegan | 2.0 | 14.4 | 2.3 | 172.8 | 23.4 | 1 | 17 | 59 | 507 |
| PROD | halve waste | BAU | 8.3 | 12.7 | 1.9 | 160.1 | 21.5 | 0 | 3 | 41 | 103 |
| PROD | halve waste | reference | 4.1 | 12.7 | 1.9 | 151.7 | 20.0 | 1 | 9 | 33 | 270 |
| PROD | halve waste | pescatarian | 2.5 | 12.4 | 1.9 | 149.3 | 19.8 | 1 | 9 | 34 | 281 |
| PROD | halve waste | vegetarian | 2.5 | 12.5 | 1.9 | 148.0 | 19.5 | 1 | 10 | 36 | 317 |
| PROD | halve waste | vegan | 1.6 | 12.3 | 2.0 | 144.6 | 19.2 | 1 | 12 | 40 | 358 |
| PROD+ | full waste | BAU | 8.7 | 13.1 | 2.2 | 147.6 | 16.5 | 1 | 10 | 61 | 292 |
| PROD+ | full waste | reference | 4.4 | 12.8 | 2.1 | 140.8 | 15.4 | 1 | 14 | 47 | 414 |
| PROD+ | full waste | pescatarian | 2.8 | 12.4 | 2.2 | 139.3 | 15.3 | 1 | 15 | 46 | 424 |
| PROD+ | full waste | vegetarian | 2.8 | 12.5 | 2.2 | 136.6 | 14.8 | 1 | 16 | 47 | 456 |
| PROD+ | full waste | vegan | 1.9 | 12.3 | 2.3 | 133.5 | 14.4 | 1 | 17 | 49 | 494 |
| PROD+ | halve waste | BAU | 8.1 | 11.3 | 1.9 | 128.2 | 14.2 | 0 | 7 | 38 | 196 |
| PROD+ | halve waste | reference | 4.0 | 11.0 | 1.9 | 121.3 | 13.1 | 0 | 10 | 28 | 290 |
| PROD+ | halve waste | pescatarian | 2.4 | 10.6 | 1.9 | 118.8 | 12.9 | 0 | 10 | 27 | 298 |
| PROD+ | halve waste | vegetarian | 2.4 | 10.7 | 1.9 | 117.6 | 12.6 | 0 | 11 | 29 | 330 |
| PROD+ | halve waste | vegan | 1.5 | 10.5 | 2.0 | 113.9 | 12.1 | 0 | 12 | 33 | 366 |

OPTM – optimization managed habitat
MAN – managed or secondary habitat
OPTN – optimization natural habitat
NAT – natural habitat

## Climate change

Several studies have analysed measures to reduce the GHG emissions related to food production. While technological and management-related options have an important role to play,[290,298,301] many studies highlight dietary change towards more plant-based diets as a measure with high mitigation potential that is likely needed to limit global warming to below 2°C.[4,5,302-304] The technological and management-related changes for reducing GHG emissions include changes in irrigation, cropping and fertilization that reduce methane and nitrous oxide emissions from rice and other crops, as well as changes in manure management, feed conversion and feed additives that reduce enteric fermentation in livestock.[298] We estimated that existing mitigation technologies and changes in management could reduce agricultural GHG emissions in 2050 by about 10%, whereas dietary changes towards more plant-based diets could deliver emissions reductions of up to 80%.[291] A further 5% reduction could be achieved by halving food loss and waste.

Staying within the boundary for climate change can be achieved by dietary changes towards more plant-based diets. Technical and management-related changes are less effective in abating food-related GHG emissions because the majority of emissions are associated with the production of animal source foods whose characteristics, such as enteric fermentation in ruminants, have limited potential for change. Ambitious dietary changes towards more plant-based diets are therefore a necessary component for staying within the climate change boundary for food production.

**#### Insert Panel 8 – The future of food in the face of climate change ####**

**Land-system change**

Future land-use changes depend greatly on agricultural yields (i.e., the output of food production per area) and the composition of crops that are demanded and produced,[244,289,296,305] which in turn are influenced by dietary choices and changes in technologies and crop management. It has been estimated that current yield trends are insufficient to meet global demand for wheat, maize, rice, and soybean if trends continue towards diets that are high in animal source foods.[306] Currently, almost two thirds of all soybeans, maize, barley, and about a third of all grains are used as feed for animals, so reductions in the portion of animal products in our diets would make the cropland associated with feed production available for other uses.[305] However, whether changing dietary preferences would result in a net decrease in the use of cropland depends also on the yields of the replacing crops, and those differences in yield might not be as favourable as one might expect, considering that investments in high-yielding varieties have been primarily directed towards major grains over the last half century.[307,308] Our dietary scenarios include large amounts of nutritionally important but relatively low-yielding crops, such as legumes and nuts.[305]

Our results indeed portray a complex picture.[291] The impacts of dietary changes (without targeted reductions in energy intake) resulted in small reductions in cropland use of 0-2%. The reason that we did not observe greater reductions from dietary change alone was that the reductions in cropland demand by countries with high portions of animal source foods were compensated by increases in cropland demand by countries that consume poor quality diets high in grains. By food group, the reductions in cropland use for feed crops was, to a large extent, compensated by large increases in cropland use for legumes and nuts which are relatively low-yielding. Redirecting investments towards higher-yielding varieties of those crops could be an effective strategy for reducing cropland use in the context of changes towards healthier diets which contain larger amounts of legumes and nuts. Our estimates of projected yield trends, and of changes in food loss and waste are more straight-forward. Based on data on yield trends and potential yield improvements across regions, we estimated that no cropland expansion will be needed if current yield gaps (i.e., the difference between current and attainable yields) were closed to about 75% percent.[244] And halving food loss and waste by 2050 could reduce cropland use by about 14%.

Staying within the boundary for cropland use can be achieved in combinations that include increases in crop yields and reductions in food loss and waste. Some dietary scenarios, e.g. the healthy reference diet with modest amounts of meat and dairy, would require ambitious improvements in yields to become feasible.

**#### Insert Panel 9 – Livestock on leftovers ####**

**Freshwater use**

Previous studies have highlighted the potential of increasing water-use efficiency by improving water management and technologies, such as irrigation systems,[309,310] as well as by dietary change towards diets lower in animal products.[311] Using data from basin-scale hydrological models,[292] we estimated that technological and management-related changes could reduce water use by about 30%, and halving food loss and waste could reduce water use by about 13%.[291] For dietary changes, we identified similar trade-offs as for cropland use. Without reductions in energy intake, water use could increase by 1-9% as reductions related to lower consumption of animal products and sugar are overcompensated by increases related to greater consumption of nuts and legumes. The lower end of the reductions is for the more plant-based scenarios that include larger amounts of water-intensive nuts and legumes.

According to our estimates, staying within the planetary boundary for water use can be achieved by combining improvements in water-use efficiency with reductions in food loss and waste. However, our analysis does not highlight regions or nations that currently face water shortage and are already above regional or national boundaries for EFRs. This is discussed in more detail in chapter 3 and panel 11.

**Nitrogen and phosphorus application**

The reduction of impacts related to the over-application of N and P fertilizers is receiving increasing interest. The discussed measures include technology-driven increases in use efficiencies,[312,313] improvements in the management of livestock and manure,[314-316] improvements in fertilizer application and distribution,[244,313,316] reductions in household waste,[315] nutrient recycling e.g. through improvements in sewage systems,[299] and dietary changes towards diets with fewer animal products.[315] In our analysis, we represented the various mitigation strategies by increases in use efficiencies, improvements in fertilizer application and distribution, and dietary changes.[291]

We estimated that increased use efficiencies and optimised application of fertilizers, including rebalancing between over and under-applying regions could reduce N and P use by about 26% for N and up to 48% for P. Reductions in food loss and waste could deliver up to 15% reduction in each nutrient, and dietary change towards healthy diets could reduce total application needs by about 10%. Staying below the upper ranges for N and P application required a combination of technological and management-related changes, dietary changes, and reductions in food loss and waste.

**Biodiversity**

Previous studies have demonstrated the impact of increasing agricultural expansion on biodiversity loss, especially in tropical counties where biodiversity rates are highest.[18,254,262] Biodiversity loss is most severe when natural habitat (e.g. primary tropical forest) is converted to agriculture, especially when compared to conversion of secondary or degraded habitats. Our results support this in that biodiversity loss was orders of magnitude higher when compared to conversion of secondary of managed habitats (Table 5).

We found that cropland use and extinction rates were synergistic with the greatest reductions occurring with technological and management-related changes and reductions in food loss and waste. The projected extinctions in our analysis show high spatial variation, with a high number of extinctions projected to occur in tropical countries and island countries with high numbers of endemic species richness. Projected extinction rates far exceed recent extinction rates[260,317] if cropland expansion occurs at the cost of existing primary habitat.

Extinction risk can be reduced through a variety of measures. First, expanding cropland into existing secondary habitat (e.g. logged forests, plantations) or other managed ecosystems (e.g. pastures and rangelands) reduces the number of species lost by >90%. Second, adopting technologies and management related changes has the greatest potential of reducing global biodiversity loss (~75% relative to the BAU) because of the reductions in cropland expansion. Third, halving food loss and waste can reduce the projected biodiversity loss by as much as 33% relative to the BAU scenario and has a relatively smaller potential to benefit biodiversity.

We found that adopting the reference healthy diet (or one of its variations) could increase the global number of extinctions if land-use change occurs in areas of current production. This is mainly a result of 1) increased caloric intake to the recommended 2500 kcal capita$^{-1}$ day$^{-1}$ in the reference diet in countries where the consumption levels are below this and 2) shifting production priorities to produce crops (e.g. nuts and pulses) needed to support the reference diet. These results assume, however, that a proportion of the additional demand will be met by domestic production. A rebalancing of regional production based on biodiversity concerns could mitigate those additional stresses (OPT scenarios in Table 5). Our models support other research and demonstrate that rebalancing or optimizing global land use based on biodiversity concerns could have the single greatest impact on reducing biodiversity loss. [305,318] Results from all of our optimization scenarios and their impact on each boundary can be found in Supplementary Table 6.

The biodiversity boundary can only be met when adopted measures are in line with our strategic directions for high-order transformations of the global food system (see chapter 3). Other measures that should be adopted include; establishment of new protected areas;[319] expansion and increased enforcement of protected areas in key biodiversity areas;[319-321] increasing international trade from higher yielding and less diverse nations to lower yielding and more diverse nations,[18,322-324] and minimizing agricultural expansion into species rich areas.

## Sensitivity analysis

We undertook a series of sensitivity analyses to identify additional dietary aspects of importance for staying within the boundaries for food production. For that purpose, we varied the composition of the reference diet by changing its meat and dairy content, and we assessed the importance of scale effects by considering a scenario of lower caloric intake (Table 6). Increasing the limit on red meat intake from one 100 g serving per week to three (the current recommendation put forward by the World Cancer Research Fund for lowering the cancer-related risks of red meat consumption[325]) led to a near doubling of food-related GHG emissions and total environmental impacts comparable to those of the business-as-usual pathway. Increasing milk consumption from 250 g/d in the reference diet to 500 g/d (a level still below current US dietary guidelines) led to a more than 40% increase in GHG emissions and total environmental impacts that exceeded those of the BAU scenario for cropland use, freshwater use, and nitrogen application. Neither scenario could be combined with technical and management-related changes to become a feasible combination that would stay below the boundaries for food production. In contrast, reducing caloric intake from 2500 kcal/d to 2100 kcal/d, a value assuming that body mass index is reduced to 22 kg/m$^2$ globally, which is in line with WHO recommendations on healthy body weight and physical activity levels,[326] reduced environmental impacts by up to 14% and resulted in total environmental impacts that were significantly lower than those of the BAU projections.

**Table 6.** Environmental impacts of increased meat (ref high meat) and milk (ref high milk) consumption above those recommended by the reference diet and reduced caloric intake to 2100 kcal/day (ref low cal). The colours illustrate whether environmental impacts transgress the food production boundaries: green - below lower range value; light green - below or equal to boundary but above lower range value; orange - above boundary but below upper range value; red – above upper range value.

| Production (2050) | Waste (2050) | Diet (2050) | GHG emissions ($GtCO_2$-eq $yr^{-1}$) | Cropland use (M $km^2$) | Water use ($km^3$) | N application (Tg N) | P application (Tg P) | Biodiversity loss (E/MSY) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Food Production Boundary** | | | **5.0 (4.7-5.4)** | **13 (11.0-15.0)** | **2.5 (1.0-4.0)** | **90 (65.0-130.0)** | **8 (6.0-16.0)** | **10 (1-80)** | | | |
| | | | | | | | | **OPTM** | **MAN** | **OPTN** | **NAT** |
| **BAU** | halve waste | ref high meat | 6.7 | 18.7 | 2.8 | 168.9 | 23.0 | 2 | 36 | 108 | 1029 |
| **PROD** | halve waste | ref high meat | 6.0 | 13.0 | 2.0 | 158.7 | 21.4 | 1 | 9 | 41 | 268 |
| **PROD+** | halve waste | ref high meat | 5.9 | 11.5 | 2.0 | 127.0 | 14.2 | 0 | 15 | 37 | 403 |
| **BAU** | halve waste | ref low cal | 4.3 | 16.1 | 2.3 | 147.2 | 19.0 | 1 | 22 | 81 | 647 |
| **PROD** | halve waste | ref low cal | 3.9 | 11.4 | 1.6 | 137.3 | 18.1 | 1 | 8 | 33 | 246 |
| **PROD+** | halve waste | ref low cal | 3.8 | 9.7 | 1.6 | 109.3 | 11.6 | 0 | 5 | 28 | 170 |
| **BAU** | halve waste | ref high milk | 6.7 | 18.8 | 2.6 | 171.3 | 22.7 | 2 | 34 | 109 | 983 |
| **PROD** | halve waste | ref high milk | 6.0 | 13.3 | 1.9 | 161.4 | 21.4 | 1 | 10 | 43 | 299 |
| **PROD+** | halve waste | ref high milk | 5.8 | 11.4 | 1.9 | 130.0 | 14.3 | 1 | 11 | 39 | 309 |

OPTM – optimization managed habitat
MAN – managed habitat
OPTN – optimization natural habitat
NAT – natural habitat

## Implications for future food production

Aligning future diets with the reference diet (Table 1) will require significant changes in what foods are produced globally (Figure 10). For example, a shift to the reference diet and halving food loss and waste would need an increase in global legume production by more than 210% and in the production of nuts and seeds by 170%. In comparison, the expected growth of these crops along a BAU pathway would imply an increase of legumes and nuts of only 83% and 46%, respectively. A shift to the reference diet and halving food loss and waste would imply substantial reductions for beef (65%) and pork (85%), compared to large expected projected increases in production along a BAU pathway. Seafood production, on the other hand, is predicted to increase by 48% in a BAU pathway but nearly 120% if the reference diet is adopted globally. This highlights the potential importance of seafood as a protein source in the future and the need for developing sustainable production practices (Panel 10).

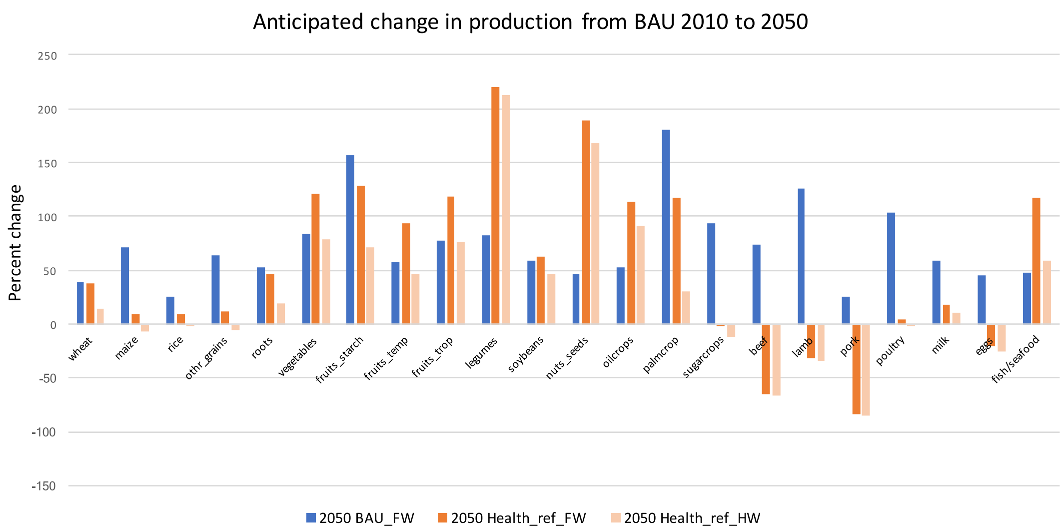


**Figure 10.** Predicted change in production by 2050 (percent from the BAU 2010 scenario) for the BAU and the healthy reference diet, full and half waste scenarios, respectively.

**#### Insert Panel 10 – The role of seafood in global diets ####**

## Uncertainty in the modelling results

Throughout the report we have addressed uncertainties that exist in our estimates of the scientific targets for healthy diets and sustainable food production. In line with previous uncertainties, we have a much higher level of certainty in the overall direction and approximate magnitude of the relationships presented in Table 5 than about specific quantitative details. For example, we can be fairly certain about the trend of decreasing rates of biodiversity loss with dietary changes and improved production practices. However, we are less certain about the exact number of species that will be lost for each scenario and each dietary change. This is also the case for the other control variables in that we are less certain in the specific numbers resulting from each scenario but have much higher certainty in the trends of decreasing environmental impact with improvements in production practices, reduction in food loss and waste, and shifts toward healthy diets.

The role of innovative technologies[327] that are not yet proven at scale but might become operational at some point in the future were not specifically investigated by this Commission given the limited data available on the environmental impacts of those technologies. Some examples of potential game changers include using insects, algae and microbes as animal feed,[23,328] laboratory-cultured meat[329]. In our report, we chose to focus on solutions that are readily available today but might not have been deployed at scale.

# Chapter 5 – A framework for a Great Food Transformation

## Lessons from past successful global transformations

The EAT-Lancet Commission does not underestimate the gravity of its message or the urgency of the task. They are in line with international reviews of different aspects of global food systems over the last decade.[3,330-340] The Commission envisages what is needed as nothing less than a Great Food Transformation. By transformation, we mean a substantial change in the structure and function of the global food system so that it operates with different core processes and feedbacks.[341] This transformation will not happen unless there is widespread, multi-sector, multi-level action to change what is eaten, how it is produced and its impacts, while ensuring healthy diets for all.

There is no magic 'fix' to the problems the Commission has explored. They require hard work, political will and resources. There are unlikely to be any simple or 'one shot' technical fixes, and opponents will warn of unintended consequences or argue the case for action is premature or left to existing dynamics. The Commission disagrees. ***The data are both sufficient and strong enough to warrant action*.** Delay will increase the likelihood of serious, even disastrous, consequences. We are clear, too, that the approaches taken in the Great Food Transformation should be guided by the scientific targets that define the safe operating space for food systems: the mix of healthy diets and planetary systems and processes which underpin human health and environmental sustainability. Simply to focus on one at the expense of others would be self-defeating.

Humanity has never before set out to change the food system so radically at this scale or speed. There have been major national food system transformations in the 20th century by countries such as China, Brazil, Vietnam and Finland[342-344] from which to draw lessons. The world's diet has also been shown to be able to change relatively rapidly. Within a few decades countries have changed diets, going through a nutrition transition, some of whose dynamics such as sweetening are now clear.[345]

Wars and disasters also provide ominous lessons, both of destructive effects and of seizing opportunities from the ashes of grim experience. Arguably, only at the end of World War 2 was there the kind of global effort and commitment to redirect the food system that this Commission believes now is necessary.[346,347] New institutions were created or revised at the global level such as the WHO, FAO and World Bank which allied with new and renewed national Ministries of agriculture and health to banish the pre-War food problems caused by market distortions, environmentally damaging farming, and social inequalities.[346,347] However, the negative consequences of the post-war food revolution are now becoming increasingly clear. The data addressed in this and other reports poses a more complex array of problems, which now require a new vision. A second food revolution – a Great Food Transformation – is needed.

The Commission proposes that, while wars and disasters do shape subsequent history, our evidence offers the chance to anticipate events and to shape better outcomes. Encouragement can be drawn from previous, daring thinking and action in history. Table 7 lists some examples where science has informed and / or led global transformations. None are as extensive as the Great Food Transformation must be, but optimism and some lessons can be derived.

The first lesson from past global transformation is that no single actor or breakthrough is likely to catalyze systems change. Systems change is by definition extensive and will therefore require actors at all scales and in all sectors engaged and working toward a shared set of goals. This lesson lies at the heart of Sustainable Development Goal 17 which recognizes that a "*A successful sustainable development agenda requires partnerships between governments, the private sector and civil society. These inclusive partnerships built upon principles and values, a shared vision, and shared goals that place people and the planet at the centre, are needed at the global, regional, national and local level*."

## TABLE 7. Reasons to be cheerful: examples of Systems Change / Systemic Action

| *Issue* | *Location* | *The problem* | *Timing* | *Action* | *Recipe for multi-level intervention* | *Success?* |
|---|---|---|---|---|---|---|
| **Food supply** | Global | The 1920 - 30s food system exhibited major problems of hunger, inequality, environmental damage and political upheaval. | The US Dust Bowl.[348,349] Recession-led hunger and famine, exacerbated by war (e.g. Soviet Union 1932-3; Bengal India; UK 1936).[350-353] | Hot Springs Conference 1943 began the mapping;[346] FAO created in 1945; Widespread food welfare programs e.g. in schools.[354] | Policy pressure from health, agriculture and social research combined with political will across ideological divides to build global, national and local (farm/citizen/ school) level action. | A transformation of world food supply followed, but it came at the cost subsequently noted as threats to eco-systems and the growth of new diet-related ill health. |
| **HIV Aids** | Global | c.70 million people affected since outbreak; 35 m deaths from HIV; 36.7 m living with HIV Aids.[355] | Almost certainly first emerged in1940s, and identified with male-to-male sex in the USA in 1970s . | 1983 virus identified. Antiretroviral therapy (19.5m people in 2016); prevention of mother-child transmission; facilities for testing and counselling.[355] | Sound data and research; mass education programmes; peer-to-peer learning; pharmaceutical development; finance support. | Containment is possible. No eradication yet. More success in affluent countries with infrastructural support. |
| **Tobacco controls** | Global | Causal link between smoking tobacco and premature death from preventable disease. | Causal link between smoking tobacco and lung cancer shown in 1952. | Years of action lead to WHO Framework on Tobacco Control, a treaty adopted at 56th World Health Assembly, May 2003 - the first World Health Organization treaty adopted under article 19 of the WHO constitution. | Decades of research showing link between smoking and disease; patient organization neutralizing opposition; a mix of fiscal and educational programmes; mix of actions from global to individual.[356] | Clear evidence for action plus wide support for controls but the product is still legally available and widely used. |
| **Trans-fatty acids in the food supply** | Global | Industrially produced trans fatty acids ('trans fats') contribute to premature death from heart disease of 500,000 people annually.[357] | First noted in 1950s,[358] with 1970s research meeting strong resistance from vested interests, solid research from the 1980s showed the health impact of trans fats.[359] | 2015 decision by US Food & Drug Administration to ban trans fats; 2018 call by WHO for global elimination; restrictions or bans in Denmark, Switzerland, Canada, Britain and USA. | Public health concerns are beyond doubt. WHO endorses a REPLACE strategy. Food industries recognize alternatives. | The movement to remove and/or reduce trans fats is accelerating worldwide. |
| **Energy shift** | Global | Fossil fuels are a source of Greenhouse Gas emissions, and were noted as potential disruptors of the carbon cycle. | Oil becomes major fuel source in mid 19th century. The assumption that oceans would absorb excess carbon was questioned in late 1950s. | Alternative energy R&D; public awareness; scientific monitoring of climate change e.g. IPCC.[360] | Research data; technology development; rise of renewable energy; cheaper alternatives; mix of mass and localized actions and interventions. | Fossil fuel use still high but rise of renewables now considered a major and growing feature of energy provision.[361] |
| **Impact of Fertilizer use on water quality** | Global | Indiscriminate use by farmers; high cost; environmental impacts, e.g. run-off;[362] | Concerns about nitrogen run-off impact on various outcomes ranging from 'blue baby' syndrome, to biodiversity loss and water pollution. | A systemic approach was adopted by the European Union, in the 1991 Nitrate Directive and 2000 Water Framework Directive. These reduced nitrogen fertilizer use by 19% in 1990-2010.[363] | Inefficient use; cost savings; strong regulatory framework; public pressures; water companies working with farmers to prevent over-use. | Fertilizer use is rising again in the EU but dropping in some countries, leading to pressure to target use more efficiently. [364] |

Secondly, science and evidence-gathering are keys to change. Attention must constantly be given to what is at present a yawning gap between the evidence of food system problems and policy leverage to effect change. Yet the Commission's modelling suggests that it is possible to meet the goal of healthy diets for all from sustainable food systems. 10 billion people could be fed a healthy and sustainable diet. The gap between the present unequal, unsustainable food system and a better one can be narrowed. Interdisciplinary research and monitoring will be central in this process, not least to maintain the scale and pace of change. While long-term research is important, research is needed ***now*** to help policy actors operate on a sound basis at a pace in line with the urgency of what is known already.

The third lesson is that the full range of policy levers is likely to be needed. Faced with challenges, policy-makers' reflexes can be first to draw from the 'soft' end of possible policy interventions, such as consumer advice, information, education or, in the case of food, labelling. These kinds of interventions assume that consumer actions will generate sufficient change.[365,366] They are generally slow in impact – unless there is already mass public interest in change. However, the scale of change which must begin is unlikely to be successful if left to the individual or the whim of consumer choice. It requires reframing at the population and systemic level.

At the 'hard' end of policy intervention lies laws, fiscal measures, subsidies and penalties, trade reconfiguration, and other economic and structural measures. These alter the conditions under which the whole population exists. While the former are slow and incremental, the latter can be brusque and meet resistance. The Commission accepts that what kind of interventions are adopted is the prerogative of governments, the people and processes. Countries and authorities should not, however, *a priori* restrict themselves only to narrow measures or soft interventions. Such is the extent of change required that it is surely likely to need to draw on the full range, not just one or two policy levers.[367] Table 8 uses the Nuffield Ladder of Policy Interventions to indicate what different policy actors might do to improve dietary health from sustainable food systems. Too often policy remains on the bottom 'soft' rungs 1-3 of the policy ladder.

The policy terrain indicated by this Commission is very broad. Faced with immense challenges, some argue that it is best to refine attention to just a few 'winnable' targets. We disagree. A shared, planetary overview requires a parallel extensive policy umbrella. The vision we offer here, with scientific targets for healthy diets and sustainable food production inevitably takes food, health and environmental policy into many policy areas, ranging across trade, economics, rural livelihoods, equity, culture, social and community policies.[368] This is a strength not a diffusion of effort. For the food system to change, and for healthy diets to be available to all requires not just food production or consumption to change but sectors in the middle of the food chain such as food processing, storage, logistics, retail and food service. They need to be engaged in the transformation, not least because economic power and cultural influence within current food systems often resides with these intermediary sectors.[369-371] The Commission therefore calls for more work on these stages of global food systems.

**Table 8. Applying the Nuffield Ladder of Policy Intervention to Health Diets from Sustainable Food Systems**

| ***Policy rung*** | ***Policy Option*** | ***Level of intervention*** | ***Description*** | ***Indicative Government role*** | ***Indicative Industry role*** | ***Indicative Civil Society role*** |
|---|---|---|---|---|---|---|
| 8. | Eliminate choice | ***'HARD'*** | Channel actions only to the desired end and isolate inappropriate actions | Set goals for a zero negative impact food system | Withdraw inappropriate products; diversify the business | Win public support for elimination of unhealthy diets |
| 7. | Restrict choice | | Remove inappropriate choice options | Model 'choice-editing' / rationing on a population scale. | Allocate funding to favour sustainable and healthy products | Campaign for banning and pariah status of key products and processes |
| 6. | Guide choices through disincentives | | Apply taxes or charges | Develop multi-criteria interventions, building on existing developments such as carbon and sugar taxation, and scoping others such as marketing controls, carbon-calorie connections. | Use of contracts and conditions to shape supply chains | Disinvestment campaigns |
| 5. | Guide choices through incentives | | Use regulations or financial incentives | Inter-agency, cross government engagement with the consuming public | Consumer reward schemes | Build cultural appeal for healthy diets from sustainable food systems |
| 4. | Guide choice by changing default policy | | Provide 'better' options | Recognise the problem but not give it high priority | Already being pioneered by retailers in their own-label products, and by in food service actors through menu planning, reformulation | Legislative change campaigns |
| 3. | Enable choice | | Enable individuals to change behaviour | The market economics position, currently manifest via logos and branding appeals | Focussed marketing on only healthy and sustainably produced foods | Campaign for alternative products |
| 2. | Provide Information | | Inform or educate the public | Mass, public information campaigns | Prioritisation of brands which appeal to eat differently, | led by NGOs, brands and some commercial interests |
| 1. | Do nothing | ***'SOFT'*** | No action or only monitor situation | The all-too common baseline of inactivity, which can be maintained by vested interest support | Rely upon public relations / media advisors to alert as to coming difficulties | Ignore the wider picture and stick to narrow spheres of interest |

Source: authors, after Nuffield Council on Bioethics[365]

## Five strategies for a Great Food Transformation

In addition to the general lessons that we can learn from past global transformations, we outline five readily implementable strategies and recommendations for how these could be achieved. For each strategy, there is a strong enough evidence foundation, and our modelling and analysis demonstrates their effectiveness for achieving a sustainable food system transformation. The strategies offered here are proposals to begin processes. As such, this chapter does not provide an exhaustive nor prescriptive list of actions. Rather, these are presented as indicative entry points for further context-specific national, regional, city and local change. This chapter also makes no distinction between short- and long-term strategies, mindful that countries at different levels of economic development have great variations in political opportunities, resources, local circumstance and starting points.

### Strategy one - winning international and national commitment to shift toward healthy diets

Consumption is affected by many social, economic, geographic and political factors not addressed in this report. Shifting diets will require engaging with culture, taste, traditions and other social dimensions of food. There is the need to ensure affordability and accessibility of food, particularly in low-income countries, to change dietary norms, and to enhance knowledge of healthy diets from sustainable food systems in order to stay within the safe operating space for food systems. These diets should be at the least enjoyable and universally appealing in terms of taste, price and acceptability if necessary shifts are to occur. Physicians, public health bodies, food service leaders, civil society, and businesses need a coherent and united approach to shift the many drivers of dietary choices so that healthy diets from sustainable food systems become the aspirational eating patterns.

***Increase availability and physical access to healthy diets from sustainable food systems***

Retailers and food service shape the immediate environment in which people buy food. In high income societies, a priority is almost certainly to offer less – smaller portions, possibly less choice (who can discriminate wisely when faced by 20-30,000 food items in a hypermarket), and less packaging, as well as new, innovative packaging to preserve perishable foods.[372] Low income countries have different priorities – cutting waste on or near primary production, better logistics and storage – to increase the range and a-seasonality of foods. In both high and low income societies, public and private sector procurement standards should be guided by the need to improve diets, and appropriate access to outlets or vendors providing healthy products. Local authorities need powers to apply zoning regulations in low-income areas to restrict unhealthy food outlets.[373] Contracts and procurement policies can be used to promote healthy diets from sustainable food systems in workplaces, schools and venues where public meals are provided, but these policies need persistence and continued political leadership for success. Multiple indicators of both human and environmental health discussed in this report need to be applied.[374] Public distribution programs targeting low-income households and individuals can improve nutritional status.[375] While to date, there is little evidence that improved infrastructure or zoning regulations lead to healthy food consumption or reductions in BMI, this may be due to poor policy or evaluation design and limited data, and further research is warranted.[376] Urban planning interventions should account for local context and address the complex ways in which residents of low-income areas interact with their local food systems, such as their ability/desire to travel to different areas to buy food.[377]

In low-income countries, ensuring adequate infrastructure (e.g. roads, bridges and transportation) to remote or rural areas can also increase access as well as reduce food prices, food price volatility in local markets,[378] and food losses during transport. Agricultural extension programs that focus on both nutrition and food security can also help ensure that rural farmers and women in rural households are equipped with the information and skills they need to better obtain healthy diets from sustainable food systems.[379,380] In areas with informal markets, price incentives for street vendors to use healthier and more sustainable ingredients and investment in sanitary locations for these outlets have been recommended to increase availability of safe, nutritious food.[340]

***Increase affordability of healthy diets from sustainable food systems***
Price is a core driver of the existing food system. Primary producers are locked into demands from off the land to produce commodities cheaply but plentifully. Consumers value food being sufficiently low cost to enable them to make other domestic purchases. While low income societies spend relatively high percentages of household budgets on food, it is the reverse in high income societies. Food prices are relative to social circumstance within and between societies. That consumer food prices have become relatively more affordable has been a success of the post World War 2 food revolution. Today, some foods are under pressure to rise in price, so as to include externalities currently not included. Experimentation with sugar or soft drink taxes is one example.

The Commission agrees that food prices should fully reflect costs. As a first step subsidies on fertilizers, water, fuels, electricity, and pesticides should be critically reviewed, with some authorities arguing for their removal. Secondly, the environmental costs and societal health costs of food supply and consumption should be fully reflected in pricing by introducing taxes to reframe market signals to reflect hidden health and environmental costs. As a result, food prices may go up, so where appropriate, social protection or safety nets can be established to protect vulnerable populations, particularly children and women. At the same time, global realities mean trade must remain open. Trade plays a positive role in improving food security, nutrition through diversification of food baskets, producers, and suppliers. Trade also means that production occurs where its use of natural resource and environmental impacts can be low.

We recommend an expert panel be set up to model different economic interventions, noting the work already underway from UNEP's The Economics of Ecosystems & Biodiversity for Agriculture and Food.[381] Taxes and subsidies should encourage healthier,[382] and more sustainable diets.[383] These measures in combination limit the potentially regressive nature of either measure implemented in isolation.[384] There is significant potential for social protection 'safety nets' (e.g. increasing income through cash transfers) to improve nutrition outcomes in low-income households, but these programs must be explicitly 'nutrition-sensitive' for this potential to be fully realized.[385]

In rural areas, increasing food security can improve access to and affordability of healthy diets from sustainable food systems. Access to economic resources and poverty alleviation measures, particularly among women, are central to securing healthy diets from sustainable food systems. Market access and off-farm opportunities are essential to providing these rural farmers with the income needed to remain food secure.[386] Reducing food price volatility is particularly important to ensure affordability of healthy diets from sustainable food systems, particularly at the regional or local level. Key policies to reduce food price volatility include removing market barriers across local regions or markets; ensuring access to price information and early warning systems; implementing tighter regulations against over-speculations; international management of food stocks; revisions of biofuel subsidies and tariffs to avoid the diversion of food to energy use; and establishing social protection schemes, insurance programs and other safety nets.[387,388]

***Improve information and food marketing***

Renewed efforts by governments, industry and society are required to restrict advertising and marketing of unhealthy, unsustainable foods, and to support positive discrimination for healthy diets from sustainable food systems. This is in line with numerous calls from the 2013 WHO Global Action Plan, 2011 UN conference, 2010 WHO recommendations for marketing of food and non-alcoholic beverages to children and the WHO Ending Childhood Obesity Commission.[389-392] The INFORMAS framework is a tool that civil society and researchers can use to monitor food labelling, promotion and retail (among other) activities in a particular food environment and then compare those activities to best-practice for creating healthy food environments.[393]

***Deliver education that promotes healthy diets from sustainable food systems***

Experience indicates that education campaigns are less effective than regulatory or fiscal measures in creating sustained change, particularly when implemented without these more robust complementary measures.[394] Yet due to the significant barriers to implementing ‘hard’ regulatory measures, educational efforts may be a necessary precursor to stronger intervention and needs also to go hand in hand with it. Education on healthy diets from sustainable food systems could be integrated into schools (particularly school feeding and school meal programs), all national services, social protection programs such as cash transfer programs and peer groups (e.g. women farmer groups, co-operatives). Civil society groups, the media and other thought leaders have a leading role in increasing public knowledge of healthy diets from sustainable food systems through informational campaigns and the emergence of social movements to shift diets or reduce food waste.

***Implement food-based dietary guidelines***

Dietary guidelines that integrate health and environmental sustainability considerations could be one tool for nutrition education. To date, the introduction of such guidelines has been slow, with many countries lacking official dietary guidelines.[395] In those countries with official advice, these guidelines are rarely followed through with enabling or enforcing legislation or other policies. As such they remain as the softest kind of consumer advice rather than at mandatory or enforceable levels of standards-setting.[396] Relevant national bodies should adopt guidelines for healthy diets from sustainable food systems, backed by enabling policies and incentives and reflected through public procurement policies. Public sector organizations could work with non-governmental organizations already progressing guidelines for healthy diets from sustainable food systems.[397,398]

***Promote diets which taste good, and are culturally appropriate***
There is no need for sustainable diets to taste bad. Chefs and foodservice sectors increasingly recognize they play an important role in the Great Food Transformation. Whether designing new menus,[399-401] or taking a lead in the many national public campaigns around health and sustainability - as did 130 chefs from 38 countries on World Food Day October 10 2017, and Nordic chefs did with the New Nordic Kitchen Manifesto in 2004[402] - or pioneering peer-group education with other chefs via professional bodies,[403] the cooking and catering enterprise is now a key public health change agent. Good, tasty, affordable, enjoyable food can be a key ingredient in mass dietary change. Consumers can and must like and help drive the dietary shift.

***Use health care services to deliver dietary advice***
Physicians and health care service workers have important roles in education and in service delivery. These professionals can engage with others to redesign public food provisions such as school and hospital meals and to advise food service industries.[399] Health care workers also need to be equipped with the necessary information. Given the importance of the development of food preferences during the first years of life and even during gestation,[404,405] nutrition counseling (breastfeeding promotion and appropriate complementary feeding) could be integrated into maternal and child care programs. Medical education largely omits the importance of nutrition to health. Curricula should be revised and new training packages created which combine nutrition and ecosystems as determinants of health. Food services in health care facilities could demonstrate a high standard for healthy foods and beverages from sustainable food systems.

## Strategy two - reorienting agricultural priorities away from producing 'more' food and towards producing 'better' food

For healthy, sustainable diets to become the norm, it is crucial to produce food types that are the constituents of a healthy, nutritious diet, and do so in a sustainable way. Again, there are many mid-point activities which alter the healthiness of a food – the entire value chain will need to be improved to ensure that nutrition gains momentum across the chain instead of being lost or diminished due to processing and packaging.[406]

***Reframe production to emphasize diet quality and functional diversity***
A fundamental reframing is needed to shift food policies from emphasizing greater volumes of outputs to an emphasis on a greater diversity of crops and the nutritional quality of foods produced. Researchers and public health professionals are raising the profile of diet quality by calling for better data to track diet quality,[407] recommending that improved diet quality assessments be developed,[408] and emphasizing the importance of diet quality to food security.[409] The Commission recommends that resources be devoted to the creation of a robust diet quality assessment tools, which could serve as a cross-cutting SDG indicator, with requisite capacity building and regular data gathering efforts at a country level. Emphasis could be placed on sustaining agricultural diversity to ensure nutrition quality through support for small and medium farms, which supply over 50% of many essential nutrients in the global food supply.[410]

***Ensure agricultural policies encourage production of nutritious foods***

Agriculture is a main determinant of nutrition, and it has been recognized that national and global agricultural policies should work to enhance nutrition outcomes.[411] Actions can include providing incentives for primary producers to produce nutritious and plant-focused foods, focusing agricultural research investments on identifying pathways for increasing nutrition and sustainability or developing programs to support diverse and environmentally sustainable production systems. Because evaluations of the effectiveness of agricultural policies on nutrition and health outcomes can be challenging, greater resources need to be directed at developing high-quality evaluations of the impact of upstream policies on nutritional outcomes.[412]

***Support 'less and better' animal production***

The growing demand for animal source foods puts pressure on land use, increases GHG emissions, and if grain-fed, is also water intensive.[4,5,18,303] However, in some contexts, animal production can also be core to supporting livelihoods, grassland ecosystem services, poverty alleviation, and nutritional status benefits (particularly in children and vulnerable populations).[413] As such, animal production needs to be considered in a specific context to understand how much production should decrease in a given environment, and what role sustainable practices (e.g. increasing feed use efficiency[414] and reducing feed-food competition) that also support a broader range of considerations such as animal welfare and antimicrobial resistance can play. There is an emerging discourse exploring what 'less and better' means in different contexts.[415] We support the continuation of this holistic evaluation of the context-specific trade-offs or win-wins that could arise from animal production (see Panels 2 and 9).

## Strategy three - sustainably intensifying food production, generating more high-quality output

A key element of sustainable intensification is closing existing yield gaps while capturing environmental benefits of production systems. As measures that boost productivity could incentivize producers to expand production onto new land, strict land use controls (discussed below) must also be implemented. Solutions will vary by country depending on factors such as natural resource endowment and climatic conditions.

***Adapt cropping to bioclimatic conditions***

Agricultural practices could be adapted to soil characteristics, water availability and climatic drivers of evapotranspiration.[416] For example, in arid regions, drought tolerant crop varieties could be selected, adequate cropping pattern could be used, and deficit irrigation (only applied during the drought-sensitive growth stages of a crop) and supplemental irrigation (applied to complement rainfall) could be applied.[417-421] Local to global scale land use planning incorporating these considerations could improve sustainability of food production, but complementary measures might also need to be incorporated to ensure these regions have access to a diverse range of nutritious foods (see Trade Panel 11). In addition, matching production practices to local conditions can increase food production sustainably.[422]

**#### Insert Panel 11 – Free trade and food ####**

***Practice precision agriculture***

Precision agriculture techniques could be scaled up and subsidized. To obtain more 'crop per drop' of water, it is key to select the right crop cultivar planted at the right density, time and rotation, to practice water capture (for a higher reliance on green water), soil restoration, as well as drip irrigation combined with soil water harvesting and soil conservation practices.[416] This will mean reducing nutrient applications in some countries and increasing applications in others. Technologies needed for precision agriculture currently are expensive, hence private sector companies have a role in scaling them up for affordability and governments should provide subsidies to enable their adoption in lower and middle-income countries.

***Close nutrient loops***

Practices to prevent nutrient losses from the farm include no/low tillage, using N-fixing cover crops or crop varieties with greater root mass, rotational grazing, crop residue management or field margin management such as riparian forests.[423] Further examples include recycling and efficient use of manure and soil erosion control measures (e.g. buffer strips to intercept both soils and nutrients).[424-429] Additional on-farm measures include covered manure storage, anaerobic digestion for adjustment of nutrient ratios to better match crop needs, and biogas production from manure (possibly to power on-farm machinery).[301,430,431] Larger-scale measures include recycling nitrogen and phosphorus from wastewater systems, cities, agriculture and industry, and implementing governance mechanisms to ensure regional compliance with water and air quality targets related to reactive nitrogen and NOx formation.

***Redistribute fertilizer use***

Redistributing fertilizer from over- to under-applying regions would increase global food production and improve nutrient use efficiency and water quality.[244] Increasing nutrient inputs in regions with already high nutrient inputs tends to increase agricultural runoff and reduce nutrient use efficiency and water quality.[432-434] In over-applying regions, regulations could be used to mandate water quality targets. For example, after the EU Nitrates Directive was put in place to limit nitrate concentrations in water, decreases in fertilizer use in the EU have been associated with increases in water quality.[435] In under-applying regions, subsidies that increase access to fertilizer can increase yields.[436,437]

***Turn agriculture into a carbon sink***

Huge increases in carbon sequestration in agricultural soils and above-ground are needed[37,438] and can be achieved through various measures. Such measures include incorporating farm organic wastes into the soil, low/no tillage, nitrogen-fixing cover plants, replacement of annuals with perennial crops and pastures, agroforestry, establishing buffer strips and keeping some farmland under natural vegetation. These measures may come at a cost to near-term yields and thus to the farm economy, calling for significant policy support and financial incentives. The 10% conservation in agriculture recommended in Chapter 3 can in many contexts serve multiple roles including carbon capture, nutrient interception, and habitat and corridors for biodiversity (e.g. riparian forests).

***Include agroecological practices***

Biodiversity conservation is essential to maintain ecosystem services that support agriculture. In addition to land sparing measures proposed in the previous section, practices that enhance biodiversity *within* agricultural systems are needed, e.g. riparian buffer strips or flower field margins. The presence of natural enemies from increased biodiversity *within* agricultural systems could prevent yield losses by contributing to integrated weed, pest and disease management and could increase crop yields via increased pollination by natural pollinators.[439,440] *Sparing* remaining intact ecosystems is essential to achieving the climate and biodiversity boundaries described in Chapter 3, but it is also evident that *sharing* space for biodiversity in production landscapes is necessary to secure biodiversity's contribution to food production including pollination, pest control, carbon capture and regulating water quality.

## Strategy four - Stronger and coordinated governance of land and oceans

To ensure that the food production boundaries are not surpassed, management of land and oceans is vital. Land management needs to be based on an assessment of the conservation, production/grazing, or restoration value of the specific region. On land and in marine systems, stronger support for the protection of key biodiversity areas, and intact ecosystems is urgently needed. Intact ecosystems that do not benefit from official protection status need biodiversity conservation and climate compatible management options that respect the rights of indigenous communities. Management of the world's oceans needs to ensure a future supply of wild fish and other seafood and at the same time stimulate an expansion of marine aquaculture without compromising key sustainability dimensions.

***Halt expansion*** **of new agricultural land at the expense of natural ecosystems.**
Direct regulatory measures include strict protections on intact ecosystems, suspending concessions for logging in protected areas or conversion of remaining intact ecosystems, particularly peatlands and forest areas. Other measures include land use zoning, regulations prohibiting land clearing and incentives for protecting natural areas including forests. Approaches that extend beyond the public sector, such as community forest management, can also promote conservation,[441] but their effectiveness varies greatly across contexts.[442,443] There has been recent enthusiasm for private sector approaches (market-based instruments), but these do not substitute for regulatory governance structures.[444] The boundary of zero net agricultural land expansion does allow for some local expansion in defined contexts. Of particular importance is to implement and enforce policy mechanisms that ensure that any agricultural expansion occurs in existing managed forests (e.g. plantations), abandoned agricultural areas or other managed ecosystems rather than expanding into natural habitats and other species-rich areas.[305,318] Conversion within agricultural land also matters, and trade-offs among multiple ecosystem services (e.g. potential biodiversity loss and/or potential reduction in GHGs when shifting land uses) need to be considered.[445]

***Establish international land use governance***
Unprecedented levels of collective action at the local to global level are needed to stay within the boundary of zero net land use. Coordinated, international governance across national borders is needed to minimize 'deforestation leakage', or the phenomenon of stronger land controls in one region encouraging agricultural expansion and land conversion in other areas with weaker land use governance, less monitoring and lower enforcement.[446] At the regional and local levels, pairing sustainable yields intensification with governance and establishment of conservation areas is vital to preventing land use expansion, conserving biodiversity in production landscapes, and protecting the well-being of indigenous communities and shareholders who are dependent on the land in question.[447]

***Restore, reforest and afforest degraded land***
Where appropriate, restoration of degraded land can be promoted through financial incentives for landholders to undertake restoration projects or even sanctions for landholders who fail to initiate restoration of their land.[448] Active restoration techniques include soil management, planting, or using thinning or burning as a means to speed up vegetation recovery. These approaches have been favoured by decision-makers and implementers in the past, yet they are often costly and not always best suited to the area.[449] For example, in tropical forests, natural regeneration can perform better than active restoration to promote biodiversity and natural vegetation structure.[449] Given different contexts, policy makers should determine which approach, or what mix of natural and active restoration approaches, are best suited for a specific ecological conditions.[449] The global restoration movement could be supported through political commitment to existing frameworks, such as the Bonn Challenge and the Convention on Biological Diversity's Aichi Targets.[450,451]

***Manage oceans***
Rigorous aquatic ecosystem governance is fundamental for protecting marine biodiversity as well as ensuring ecosystem functions and a continued future supply of wild seafood.[21] The 'ecosystem approach to fisheries and aquaculture' (EAF/EAA)[452,453] should to be implemented, implying use of the Code of Conduct for Responsible Fisheries.[454] Harmful subsidies to world fisheries will need to be removed, as these lead to over-capacity of the global fishing fleet.[455] In accordance with SDG no 14, by 2020 at least 10% of marine areas should be closed to fishing. Focus should lie on closure of high seas areas, thereby using the high seas as a fish bank. This has the capacity to greatly reduce the inequality of both volume and value distribution of global fisheries, and simultaneously to increase net gains of most coastal countries, including the least developed.[456] Other essential measures include a general prevention of overfishing and application of the precautionary approach where lack of scientific information regarding a fishery's impact on marine species and ecosystems not is to be considered an excuse for delaying crucial action.[453] Moreover, there is a need to manage future risks and opportunities related to an anticipated aquaculture expansion. This includes implementation of strict regulation on where to locate new operations, antibiotic and chemical use, nutrient runoff and application of sustainably sourced feed from terrestrial and marine origin. Seafood transparency and eco-certification schemes can also be viable mechanisms for improving the performance of the expanding seafood sector.[457]

## Strategy five - at least halving food losses and waste, in line with global sustainable development goals

Food losses and waste (FLW) occur at all stages along the food supply-chain, and occur for different reasons in low-, middle and high-income countries, highlighting the need for context-specific strategies.[335] Given the emphasis on food production and end-consumption in this report, the proposed actions to reduce FLW focus mainly on these two extremities of the food life-cycle, though adopting a whole life-cycle approach to FLW reductions will be necessary.[458] Governments, local officials, investors, producers, researchers, innovators and private sector companies are needed to develop, finance and support solutions across the supply chain. Particularly where the solutions are expensive, resource intensive or implemented in low- or middle-income country settings.

***Improve post-harvest infrastructure, food transport, processing and packaging***
FLW at the initial production stages are generally highest in low- and middle-income countries.[459,460] These can result from poor harvest scheduling and timing, rough or careless handling of produce or lack of market access. Inadequate cooling and storage facilities can drive farmers to leave crops unharvested or in the fields, which thereby increases the risk of rotting and contamination. Increased investment in post-harvest infrastructure can help reduce some of these FLW.[461] Investment in processing technologies such as drying and packaging solutions are also needed. Measures to reduce FLW at intermediate stages of the food value chain are detailed elsewhere.[459]

***Increase collaboration***
Steep reductions in FLW will require cooperation among multiple food system actors in order to assess sources of FLW and develop targeted solutions. Examples such as the Save Food Initiative has been used to develop policies, strategies, programmes and financing strategies for reducing FLW.[462] Infrastructural solutions include initiating collective storage facilities, developing food processing technologies and infrastructure or investing in cold chains.[459]

***Train and equip producers***
Growers can be encouraged to adopt on-farm practices to reduce FLW, such as good animal hygiene (reducing the risk of contamination) or better harvesting and storage techniques. To build this capacity of producers, investment in education, training and extension services is needed. Given the high involvement on women in post-harvest handling (along with many other activities),[463] these services should specifically be designed to engage with and be accessed by women producers in developing countries.[459]

***Educate individuals***
Particularly in highly-developed countries, the public is responsible for a large proportion of food wasted.[460] The Commission envisages use of campaigns to promote better planning of purchases, better understanding of 'best before' and 'use by' labels, better storage practices, better evaluation of portions needed, better food preparation techniques, and better knowledge of how to use 'leftovers'.

***Use public policy mechanisms***
Appropriate public policy can be one mechanism to achieve the previously listed actions. FLW can be incorporated into national waste policies, food safety policies, food standards rules, food labelling regulations, food redistribution policies and food subsidies.[459] Financial incentives or national waste reduction programs can encourage collaboration or national innovation competitions among actors to reduce FLW in their specific supply chains.

## Tools for a Great Food Transformation

The evidence provided in this report suggests that the steps to begin this Great Food Transformation should be taken quickly. Moving toward this Transformation requires good data on each country's status, across the various criteria and indicators that capture the health of its population's diets, and the sustainability of their food systems. Each country or administrative unit – region, city, continent – must conduct assessments of their diet and food system. These are essential for governance mechanisms to deliver systemic change. Countries vary in current diets, the impact of their food systems, and the particularities of their immediate challenges. Opportunities to act inevitably differ across contexts. There are huge variations in resources, networks of actors, institutions, and legislative tools available to support transformation.

In those countries that lack basic infrastructure and technologies that are given in the developed world and which are basic precursors to sustainable food supplies, essential non-food policies must first be developed and implemented. Despite these varying starting points, there are common tools, outlined below, that can be used to spur the Great Food Transformation.

**Clear articulation of goals**
While different priorities and pathways need to be tailored to different contexts, they all need to encourage the global trajectory toward a single set of shared goals. The work of this Commission has been to set scientific targets for both healthy diets and sustainable food systems. Gaining consensus on these targets is a first step in galvanizing actors around a common agenda. Then the targets will be refined and engaged with at all policy levels.

**Adoption of an integrated approach**
Because these goals cross-cut political, sectoral and geographical boundaries, an integrated approach is needed. An integrated policy approach means that everyone works to progress a shared set of goals leading to healthy diets from sustainable food systems. This will require working across siloes and making connections across all sectors and parts of society.[407] Integrated approaches can be advanced by establishing formal and frequent interactions between governing groups. For example, UN bodies should facilitate inter-institutional working groups and meetings that focus on cross-sectional issues, such as sustainable diets. Collaboration by FAO, UNEP, UNESCO, and UNDP on the Intergovernmental Panel on Ecosystem Services (IPBES) is exploring a specific assessment on food and food systems.

**Firm institutional leadership and governance**
Engineering change across the food system – if that is narrowly conceived as the economics of supply chain management – is complex enough, but if multi-level, multi-actor, multi-sector, multi-disciplinary change is required, this poses a serious challenge to governance. In a world where many governments have adopted laissez-faire approaches to consumer choice, the leadership now required by both governments and food system actors is considerable. This demands co-ordination, consultation and good policy facilitation by significant policy actors.

**Use of the full range levers – policy and otherwise**
Too often, attempts to change diet or food systems confine themselves to a soft policy approach. Experience from other public health or environmental issues indicates that education campaigns, community empowerment initiatives or private sector voluntary commitments may be less effective than policy tools such as regulatory or fiscal measures in generating sustained change, particularly when implemented in isolation.[394] As was stated earlier, the full range needs to be available, from ‘hard’ to ‘soft’, from fiscal and legal measures to education and information measures. While government has a crucial role, the private sector and civil society must be engaged,

using the levers and capacities which only they have such as marketing, thought leadership, public engagement, supply data and management, quality control, and food market data.

**Finance policy instruments that support healthy diets from sustainable food systems**

Domestic spending will need to increase for policy instruments supporting healthy diets from sustainable food systems. The lack of dedicated funding to support the transformation toward more sustainable food systems is recognized as a critical barrier to progress.[464] There are opportunities to leverage existing investment flows in innovative ways in order to create multiple wins across the sustainable development challenges we face today. Donors and multi-lateral organisations should be engaged, and OECD reporting processes could be refined in order to better track this funding.[407]

**Unprecedented coordination of efforts**

A great challenge before us is building an alliance of progressive forces which can operationalize the Commission's broad recommendations. These alliances could include actors at all stages of the food system as well as operate at all scales so that local actions can be in line with global goals. In order to achieve a deeply integrated agenda for food, alliances could focus on including both the 'usual' food system actors (e.g. farmers, food industry and policy makers), as well as those actors working primarily outside the realm of food systems but that have overlapping goals, e.g. conservation,[465-467] anti-hunger,[468] animal welfare,[469,470] and social justice[471] organizations. Such alliances can play a role in bolstering support for the agenda on healthy diets from sustainable food systems and exert influence within and outside of government.

**Curation of the evidence base**

There are extensive gaps in the evidence base regarding the effectiveness of actions for shifting diets in more healthy and sustainable directions. Most actions to date have aimed to improve health rather than environmental sustainability, with very few designed to achieve multiple wins. Further knowledge gaps exist for low- and middle-income countries, where there is a dearth of evidence.[394]

**Regular monitoring and reporting**

At present, there are a number of existing annual official or officially approved reports by reputable bodies. Some health-oriented reports might be broadened to include the sustainability aspects or, vice versa, environmental or food security reports might include stronger nutritional and cultural dimensions. The alternative would be the initiation of a new annual or biannual healthy diets from sustainable food systems report, the methodology for this would need to be replicable at national and other levels. The development of sound metrics should not be allowed to become a reason to delay better reporting. In addition, monitoring and reporting should go beyond lists of actions and statistics of impacts to include regular synthesis and dissemination of lessons learned. Transferable lessons should be spread widely to inspire action and to eliminate 'reinventing' the wheel.

**Establishment of evidence-based research co-ordination bodies**

Just as the lessons from the 1920s-40s led to the creation of new international food and health institutions, so new ones may be needed today. Expert reports from existing bodies such as UN Enviroment Programme,[331] the UN Committee on World Food Security,[459] and UN Standing Committee on Nutrition have highlighted different aspects of the agenda explored by this Commission such as food's reliance on finite resources, land pressures, diet as a driver of ecosystems damage.[472] Might the urgency of recalibrating diet and sustainability of food systems be helped by a new champion? The value of bodies such as the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) is that they constantly champion the narrowing of the gap between scientific evidence and policy-making. They deliver continual, high quality data collection, while being subject to intergovernmental agreements, conventions and Conferences of the Parties (COP). The Great Food Transformation can help meet existing binding agreements such as the SDGs, the Paris Climate Change Accord, and elements of the WHO-FAO Decade of Nutrition Action, but a specific new Convention or agreement is almost certainly needed, too. The Commission recommends that international bodies review whether a new oversight body or bodies might be needed, or whether existing bodies could coalesce or have their remit and functions revised to provide the necessary focus on healthy diet for all from sustainable food systems. The diet-sustainable food system connection tends to get lost or seen as too big to tackle. Table 9 outlines possible research co-ordination bodies. Although expensive, an international body specifically focusing on healthy diets from sustainable food systems, akin to how the IPCC focuses on climate change could play a key role in curating the evidence base, synthesizing and refining existing metrics to assess healthy diets from sustainable food systems and to undertake regular monitoring and reporting to governmental and other authorities. The Table outlines other possibilities, too.

**Table 9.** Potential new evidence-based institutions which could champion and monitor the Great Food Transformation

| New Institution | Purpose | Tasks 1 | Tasks 2 |
|---|---|---|---|
| *IPCC-type mechanism for healthy diets from sustainable food systems* | To be a consortium of scientists which collates and updates data for the UN | Provide regular sources of impartial 'state of the art' summaries which combine data across disciplines | Review policy options for the UN system |
| *UN Framework Convention on Sustainable Food Systems (UNFCSFS)* | To provide a framework for healthy diets from sustainable food systems with functions akin to those of the Framework Conventions on Climate Change[473] and on Tobacco[474] | Produce guidelines and protocols which set targets and enable monitoring | Host a Food Meeting of the Parties (FOP) akin to the Convention of the Parties (COP) process |
| *International Working Party on Sustainable Dietary Guidelines* | To produce evidence-based guidelines to add sustainability criteria to existing food-based and nutrient-based dietary guidelines | Provide science-based advice for a wide range of bodies | Set healthy and sustainable dietary guidelines to meet the food-related Sustainable Development Goals |
| *A Standing Panel of Experts on healthy diets from sustainable food systems* | To be a sub-committee or standing Advisory body to an existing body such as the UN SCN or UN Codex Alimentarius Commission | Produce expert reviews of problem issues for the parent body | Advise national governments on healthy diets from sustainable food systems standards |
| *Roadmaps to healthy diets from sustainable food systems* | To generate one-off sector plans for public or private sectors or both | Industry and sector specific plans to contribute to healthy diets from sustainable food systems | Develop plans with phased processes of change to meet specific targets |
| *Global Food Systems Report* | To author an authoritative annual report, ideally under the auspices of a UN or Bretton Woods body, jointly with others | Produce an annual overview report of the world food system | Conduct special reviews attached to the Report |
| *Global Food Systems Observatory* | Consortium of scientists providing high quality evidence on interventions, modelled on the Cochrane Collaboration and Health/Obesity Observatories | Create a global working network of Universities and scientists to refine evidence-based policy | Monitor regional and national performance in line with agreed targets and criteria |

## Acknowledgements

The Wellcome Trust provided financial support for this Commission. This includes support to the secretariat to coordinate putting the report together and for fares, accommodation, and food for the Commission meetings. They also provided administrative help in hosting two Commission meetings at their offices in London. Additional support was provided by the Children's Investment Fund Foundation (CIFF) for development of the graphics and for future communications and outreach regarding the report. Both organizations had no role in the writing of the manuscript. All Commissioners were supported by their employing organizations to undertake the Commission's work. The findings and recommendations are those of the authors and do not necessarily reflect recommendations or policies of their employing organizations or of the funders. We are partnered by the Stockholm Resilience Centre and EAT and would like to thank these organizations for continuous support in putting the report together. We would like to acknowledge Per Olsson and Brian Lipinski for their comments on early draft of the report, and Theresa Marteau for acting as an advisor to the policy working group.

## References

1. Whitmee S, Haines A, Beyrer C, et al. Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–Lancet Commission on planetary health. *Lancet* 2015; **386**(10007): 1973-2028.
2. IFPRI. 2017 Global food policy report. Washington, DC: International Food Policy Research Institute, 2017.
3. Global Panel on Agriculture and Food Systems for Nutrition. Food systems and diets: facing the challenges of the 21st century. London: Global Panel, 2016.
4. Tilman D, Clark M. Global diets link environmental sustainability and human health. *Nature* 2014; **515**(7528): 518-22.
5. Springmann M, Godfray HC, Rayner M, Scarborough P. Analysis and valuation of the health and climate change cobenefits of dietary change. *Proc Natl Acad Sci U S A* 2016; **113**(15): 4146-51.
6. FAO, IFAD, UNICEF, WFP, WHO. The state of food security and nutrition in the world. Rome: FAO, 2017.
7. UNICEF, WHO, World Bank. Levels and trends in child malnutrition: joint child malnutrition estimates. Washington, DC, 2017.
8. WHO, FAO. Guidelines on food fortification with micronutrients. Geneva: WHO, 2009.
9. WHO. Global Health Observatory (GHO) data: overweight and obesity. 2018. http://www.who.int/gho/ncd/risk_factors/overweight_text/en/ (accessed 2018 4 January).
10. WHO. Global report on diabetes. Geneva: World Health Organization, 2016.
11. Zhou B, Lu Y, Hajifathalian K, et al. Worldwide trends in diabetes since 1980: a pooled analysis of 751 population-based studies with 4.4 million participants. *Lancet* 2016; **387**(10027): 1513-30.
12. Gakidou E, Afshin A, Abajobir AA, et al. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990-2016: a systematic analysis for the Global Burden of Disease Study 2016. *Lancet* 2017; **390**(10100): 1345-422.

13. Foley JA, DeFries R, Asner GP, et al. Global consequences of land use. *Science* 2005; **309**(5734): 570-4.
14. Vermeulen SJ, Campbell BM, Ingram JSI. Climate change and food systems. *Annu Rev Environ Resour* 2012; **37**: 195-222.
15. Foley JA, Ramankutty N, Brauman KA, et al. Solutions for a cultivated planet. *Nature* 2011; **478**(7369): 337-42.
16. Steffen W, Richardson K, Rockstrom J, et al. Planetary boundaries: guiding human development on a changing planet. *Science* 2015; **347**(6223).
17. Comprehensive Assessment of Water Management in Agriculture. Water for food, water for life: a comprehensive assessment of water management in agriculture. London: Earthscan and Colombo: International Water Management Institute, 2007.
18. Tilman D, Clark M, Williams DR, Kimmel K, Polasky S, Packer C. Future threats to biodiversity and pathways to their prevention. *Nature* 2017; **546**(7656): nature22900.
19. Diaz RJ, Rosenberg R. Spreading dead zones and consequences for marine ecosystems. *Science* 2008; **321**(5891): 926-9.
20. Rabalais N, Diaz RJ, Levin L, Turner R, Gilbert D, Zhang J. Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences* 2010; **7**(2): 585.
21. FAO. The state of world fisheries and aquaculture 2016. Contributing to food security and nutrition for all. Rome: FAO, 2016.
22. Pauly D, Zeller D. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nature communications* 2016; **7**: ncomms10244.
23. Klinger D, Naylor R. Searching for solutions in aquaculture: charting a sustainable course. *Annu Rev Environ Resour* 2012; **37**: 247-76.
24. Garnett T. Plating up solutions: can eating patterns be both healthier and more sustainable? *Science* 2016; **353**(6305): 1202-4.
25. Koplitz SN, Mickley LJ, Marlier ME, et al. Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure. *Environ Res Lett* 2016; **11**(9): 094023.
26. Springmann M, Mason-D'Croz D, Robinson S, et al. Global and regional health effects of future food production under climate change: a modelling study. *Lancet* 2016; **387**(10031): 1937-46.
27. Myers SS, Zanobetti A, Kloog I, et al. Increasing CO2 threatens human nutrition. *Nature* 2014; **510**(7503): 139-42.
28. Högy P, Wieser H, Köhler P, et al. Effects of elevated CO2 on grain yield and quality of wheat: results from a 3-year free-air CO2 enrichment experiment. *Plant Biol* 2009; **11**: 60-9.
29. Prior SA, Runion GB, Rogers HH, Torbert HA. Effects of atmospheric CO2 enrichment on crop nutrient dynamics under no-till conditions. *J Plant Nutr* 2008; **31**(4): 758-73.
30. Medek DE, Schwartz J, Myers SS. Estimated effects of future atmospheric CO2 concentrations on protein intake and the risk of protein deficiency by country and region. *Environ Health Perspect* 2017; **125**(8): 087002.
31. Myers SS, Wessells KR, Kloog I, Zanobetti A, Schwartz J. Effect of increased concentrations of atmospheric carbon dioxide on the global threat of zinc deficiency: a modelling study. *The Lancet Global Health* 2015; **3**(10): e639-e45.
32. Smith M, Golden C, Myers S. Potential rise in iron deficiency due to future anthropogenic carbon dioxide emissions. *GeoHealth* 2017; **1**(6): 248-57.
33. Watts N, Amann M, Ayeb-Karlsson S, et al. The Lancet Countdown on health and climate change: from 25 years of inaction to a global transformation for public health. *The Lancet* 2017.
34. Landrigan PJ, Fuller R, Acosta NJ, et al. The Lancet Commission on pollution and health. *The Lancet* 2017.

35. Gussow JD, Clancy KL. Dietary guidelines for sustainability. *J Nutr Educ* 1986; **18**(1): 1-5.
36. United Nations. Sustainable Development Goals. https://sustainabledevelopment.un.org/?menu=1300 (accessed 13 September 2017).
37. Rockström J, Gaffney O, Rogelj J, Meinshausen M, Nakicenovic N, Schellnhuber HJ. A roadmap for rapid decarbonization. *Science* 2017; **355**(6331): 1269-71.
38. van Vuuren DP, Stehfest E, Gernaat DE, et al. Alternative pathways to the 1.5° C target reduce the need for negative emission technologies. *Nature Climate Change* 2018; **8**(5): 391.
39. Rockström J, Steffen W, Noone K, et al. Planetary boundaries: exploring the safe operating space for humanity. *Ecol Soc* 2009; **14**(2).
40. Seufert V, Ramankutty N. Many shades of gray—the context-dependent performance of organic agriculture. *Sci Adv* 2017; **3**(3).
41. Clark M, Tilman D. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environ Res Lett* 2017; **12**(6): 064016.
42. IPCC. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core writing team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva: IPCC, 2014.
43. World Health Organization. Preamble to the Constitution of WHO as adopted by the International Health Conference, New York, 19 June - 22 July 1946; signed on 22 July 1946 by the representatives of 61 States (Official Records of WHO, no. 2, p. 100) and entered into force on 7 April 1948. Geneva: World Health Organization, 1946.
44. FAO. Preparation and use of food-based dietary guidelines. Geneva: World Health Organization, Food and Agriculture Organization of the United Nations, 1996.
45. U.S. Department of Agriculture, U.S. Department of Health and Human Services. Scientific Report of the 2015 Dietary Guidelines Advisory Committee. Washington, DC: U.S. Gov't Printing Offices.
46. International Food Policy Research Institute. Food systems and diets: Facing the challenges of the 21st century Washington, D.C., 2016.
47. Hic C, Pradhan P, Rybski D, Kropp JP. Food surplus and its climate burdens. *Environmental science & technology* 2016; **50**(8): 4269-77.
48. Freedman LS, Commins JM, Moler JE, et al. Pooled results from 5 validation studies of dietary self-report instruments using recovery biomarkers for energy and protein intake. *Am J Epidemiol* 2014; **180**(2): 172-88.
49. FAO. Human energy requirements. Report of a Joint FAO/WHO/UNU Expert Consultation. Rome: Food and Agriculture Organization, 2004.
50. Science NAo. Dietary Reference Intakes for Energy, Carbohydrate, Fiber, Fat, Fatty Acids, Cholesterol, Protein, and Amino Acids 2002.
51. FAO, WHO, UNU. Protein and amino acid requirements in human nutrition: report of a Joint FAO/WHO/UNU Expert Consultation. Geneva: World Health Organization, 2002.
52. Daly RM, O'Connell SL, Mundell NL, Grimes CA, Dunstan DW, Nowson CA. Protein-enriched diet, with the use of lean red meat, combined with progressive resistance training enhances lean tissue mass and muscle strength and reduces circulating IL-6 concentrations in elderly women: a cluster randomized controlled trial. *Am J Clin Nutr* 2014; **99**(4): 899-910.
53. Tomasetti C, Li L, Vogelstein B. Stem cell divisions, somatic mutations, cancer etiology, and cancer prevention. *Science* 2017; **355**(6331): 1330-4.
54. Appel LJ, Sacks FM, Carey VJ, et al. Effects of protein, monounsaturated fat, and carbohydrate intake on blood pressure and serum lipids: results of the OmniHeart randomized trial. *Jama* 2005; **294**(19): 2455-64.
55. Orlich MJ, Singh PN, Sabate J, et al. Vegetarian dietary patterns and mortality in Adventist Health Study 2. *JAMA Intern Med* 2013; **173**(13): 1230-8.

56. Satija A, Bhupathiraju SN, Rimm EB, et al. Plant-based dietary patterns and incidence of type 2 diabetes in US men and women: results from three prospective cohort studies. *PLoS Med* 2016; **13**(6): e1002039.
57. Satija A, Bhupathiraju SN, Spiegelman D, et al. Healthful and unhealthful plant-based diets and the risk of coronary heart disease in U.S. Adults. *J Am Coll Cardiol* 2017; **70**(4): 411-22.
58. Abete I, Romaguera D, Vieira AR, Lopez de Munain A, Norat T. Association between total, processed, red and white meat consumption and all-cause, CVD and IHD mortality: a meta-analysis of cohort studies. *Br J Nutr* 2014; **112**(5): 762-75.
59. Chen GC, Lv DB, Pang Z, Liu QF. Red and processed meat consumption and risk of stroke: a meta-analysis of prospective cohort studies. *Eur J Clin Nutr* 2013; **67**(1): 91-5.
60. Feskens EJ, Sluik D, van Woudenbergh GJ. Meat consumption, diabetes, and its complications. *Curr Diab Rep* 2013; **13**(2): 298-306.
61. Pan A, Sun Q, Bernstein AM, et al. Red meat consumption and mortality: results from 2 prospective cohort studies. *Arch Intern Med* 2012; **172**(7): 555-63.
62. Sinha R, Cross AJ, Graubard BI, Leitzmann MF, Schatzkin A. Meat intake and mortality: a prospective study of over half a million people. *Arch Intern Med* 2009; **169**(6): 562-71.
63. Etemadi A, Sinha R, Ward MH, et al. Mortality from different causes associated with meat, heme iron, nitrates, and nitrites in the NIH-AARP Diet and Health Study: population based cohort study. *BMJ* 2017; **357**: j1957.
64. Pan A, Sun Q, Bernstein AM, et al. Red meat consumption and risk of type 2 diabetes: 3 cohorts of US adults and an updated meta-analysis. *Am J Clin Nutr* 2011; **94**(4): 1088-96.
65. Bernstein AM, Sun Q, Hu FB, Stampfer MJ, Manson JE, Willett WC. Major dietary protein sources and risk of coronary heart disease in women. *Circulation* 2010; **122**(9): 876-83.
66. Pan A, Sun Q, Bernstein AM, Manson JE, Willett WC, Hu FB. Changes in red meat consumption and subsequent risk of type 2 diabetes mellitus: three cohorts of US men and women. *JAMA Intern Med* 2013; **173**(14): 1328-35.
67. Bernstein AM, Pan A, Rexrode KM, et al. Dietary protein sources and the risk of stroke in men and women. *Stroke* 2012; **43**(3): 637-44.
68. Kromhout D, Keys A, Aravanis C, et al. Food consumption patterns in the 1960s in seven countries. *Am J Clin Nutr* 1989; **49**: 889-94.
69. Chan DS, Lau R, Aune D, et al. Red and processed meat and colorectal cancer incidence: meta-analysis of prospective studies. *PloS one* 2011; **6**(6): e20456.
70. Bouvard V, Loomis D, Guyton KZ, et al. Carcinogenicity of consumption of red and processed meat. *Lancet Oncol* 2015; **16**(16): 1599-600.
71. Farvid MS, Cho E, Chen WY, Eliassen AH, Willett WC. Adolescent meat intake and breast cancer risk. *Int J Cancer* 2015; **136**(8): 1909-20.
72. Farvid MS, Cho E, Chen WY, Eliassen AH, Willett WC. Dietary protein sources in early adulthood and breast cancer incidence: prospective cohort study. *BMJ* 2014; **348**: g3437.
73. Song M, Fung TT, Hu FB, et al. Association of animal and plant protein intake with all-cause and cause-specific mortality. *JAMA Intern Med* 2016; **176**(10): 1453-63.
74. U.S. Department of Agriculture. nutrition.gov. September 14, 2010. http://www.nutrition.gov/.
75. Lee JE, McLerran DF, Rolland B, et al. Meat intake and cause-specific mortality: a pooled analysis of Asian prospective cohort studies. *Am J Clin Nutr* 2013; **98**(4): 1032-41.
76. Talaei M, Wang Y-L, Yuan J-M, Pan A, Koh W-P. Meat, dietary heme iron, and risk of type 2 diabetes mellitus: the Singapore Chinese Health Study. *Am J Epidemiol* 2017; **186**(7): 824-33.
77. U.S. Department of Agriculture. Dietary guidelines for Americans. Washington, DC: U.S. Gov't Printing Offices; 2010.
78. Institute of Medicine. Dietary feference intakes for calcium and vitamin D. Washington, DC: National Academy of Sciences, 2010.

79. WHO. The world health report 2003: shaping the future. Geneva: World Health Organization, 2003.
80. WHO. Diet, nutrition and the prevention of chronic diseases. Report of a Joint WHO/FAO Expert Consultation. Geneva: World Health Organization, 2003.
81. Bischoff-Ferrari HA, Dawson-Hughes B, Baron JA, et al. Calcium intake and hip fracture risk in men and women: a meta-analysis of prospective cohort studies and randomized controlled trials. *Am J Clin Nutr* 2007; **86**(6): 1780-90.
82. Feskanich D, Bischoff-Ferrari HA, Frazier AL, Willett WC. Milk consumption during teenage years and risk of hip fractures in older adults. *JAMA Pediatr* 2014; **168**(1): 54-60.
83. Guo J, Astrup A, Lovegrove JA, Gijsbers L, Givens DI, Soedamah-Muthu SS. Milk and dairy consumption and risk of cardiovascular diseases and all-cause mortality: dose–response meta-analysis of prospective cohort studies. *Eur J Epidemiol* 2017; **32**(4): 269-87.
84. W.C.R.F./A.I.C.R. Second Expert Report: Food, Nutrition, Physical Activity, and the Prevention of Cancer: A Global Perspective, 2007.
85. Aune D, Navarro Rosenblatt DA, Chan DS, et al. Dairy products, calcium, and prostate cancer risk: a systematic review and meta-analysis of cohort studies. *Am J Clin Nutr* 2015; **101**(1): 87-117.
86. Giovannucci E. Nutritional and environmental epidemiology of prostate cancer. In: Kantoff PW, Carroll PR, D'Amico AV, eds. Prostate Cancer: Principles and Practice. Philadelphia, PA: Lippincott Williams & Wilkins; 2002: 117-39.
87. Chen M, Sun Q, Giovannucci E, et al. Dairy consumption and risk of type 2 diabetes: 3 cohorts of US adults and an updated meta-analysis. *BMC Med* 2014; **12**: 215.
88. Mozaffarian D, Hao T, Rimm EB, Willett WC, Hu FB. Changes in diet and lifestyle and long-term weight gain in women and men. *N Engl J Med* 2011; **364**(25): 2392-404.
89. Mozaffarian D, Rimm E. Fish intake, contaminants, and human health: evaluating the risks and the benefits. *JAMA* 2006; **296**(15): 1885-99.
90. Virtanen JK, Mozaffarian D, Chiuve SE, Rimm EB. Fish consumption and risk of major chronic disease in men. *Am J Clin Nutr* 2008; **88**(6): 1618-25.
91. Zheng J, Huang T, Yu Y, Hu X, Yang B, Li D. Fish consumption and CHD mortality: an updated meta-analysis of seventeen cohort studies. *Public Health Nutr* 2012; **15**(4): 725-37.
92. Oken E, Radesky JS, Wright RO, et al. Maternal fish intake during pregnancy, blood mercury levels, and child cognition at age 3 years in a US cohort. *Am J Epidemiol* 2008; **167**(10): 1171-81.
93. Del Gobbo LC, Imamura F, Aslibekyan S, et al. omega-3 Polyunsaturated Fatty Acid Biomarkers and Coronary Heart Disease: Pooling Project of 19 Cohort Studies. *JAMA Intern Med* 2016; **176**(8): 1155-66.
94. Rong Y, Chen L, Zhu T, et al. Egg consumption and risk of coronary heart disease and stroke: dose-response meta-analysis of prospective cohort studies. *BMJ* 2013; **346**: e8539.
95. Iannotti LL, Lutter CK, Stewart CP, et al. Eggs in Early Complementary Feeding and Child Growth: A Randomized Controlled Trial. *Pediatrics* 2017; **140**(1).
96. Kris-Etherton PM, Hu FB, Ros E, Sabate J. The role of tree nuts and peanuts in the prevention of coronary heart disease: multiple potential mechanisms. *The Journal of nutrition* 2008; **138**(9): 1746S-51S.
97. Sabate J, Oda K, Ros E. Nut consumption and blood lipid levels: a pooled analysis of 25 intervention trials. *Arch Intern Med* 2010; **170**(9): 821-7.
98. Grosso G, Estruch R. Nut consumption and age-related disease. *Maturitas* 2016; **84**: 11-6.
99. Mayhew AJ, de Souza RJ, Meyre D, Anand SS, Mente A. A systematic review and meta-analysis of nut consumption and incident risk of CVD and all-cause mortality. *Br J Nutr* 2016; **115**(2): 212-25.

100. Luo C, Zhang Y, Ding Y, et al. Nut consumption and risk of type 2 diabetes, cardiovascular disease, and all-cause mortality: a systematic review and meta-analysis. *Am J Clin Nutr* 2014; **100**(1): 256-69.
101. Afshin A, Micha R, Khatibzadeh S, Mozaffarian D. Consumption of nuts and legumes and risk of incident ischemic heart disease, stroke, and diabetes: a systematic review and meta-analysis. *Am J Clin Nutr* 2014; **100**(1): 278-88.
102. Bao Y, Han J, Hu FB, et al. Association of nut consumption with total and cause-specific mortality. *N Engl J Med* 2013; **369**(21): 2001-11.
103. Aune D, Keum N, Giovannucci E, et al. Nut consumption and risk of cardiovascular disease, total cancer, all-cause and cause-specific mortality: a systematic review and dose-response meta-analysis of prospective studies. *BMC medicine* 2016; **14**(1): 207.
104. Estruch R, Ros E, Salas-Salvado J, et al. Primary prevention of cardiovascular disease with a Mediterranean diet. *N Engl J Med* 2013; **368**(14): 1279-90.
105. Kushi LH, Meyer KA, Jacobs DR, Jr. Cereals, legumes, and chronic disease risk reduction: evidence from epidemiologic studies. *Am J Clin Nutr* 1999; **70**(3 Suppl): 451S-8S.
106. Lee SA, Shu XO, Li H, et al. Adolescent and adult soy food intake and breast cancer risk: results from the Shanghai Women's Health Study. *Am J Clin Nutr* 2009; **89**(6): 1920-6.
107. F.A.O. Edible insects: Future prospects for food and feed security: Food and Agriculture Organization of the United Nations, 2013.
108. Asronson S. Role of algae as human food in antiquity. *Food Foodways* 1986; **1**: 311-15.
109. Arshad M, M J, M S, F S, A I. Tissue engineering approaches to develop cultured meat from cells: A mini review. *Cogent Food & Agriculture* 2017.
110. Zong G, Gao A, Hu FB, Sun Q. Whole Grain Intake and Mortality From All Causes, Cardiovascular Disease, and Cancer: A Meta-Analysis of Prospective Cohort Studies. *Circulation* 2016; **133**(24): 2370-80.
111. Hu FB. Are refined carbohydrates worse than saturated fat? *Am J Clin Nutr* 2010; **91**(6): 1541-2.
112. Dehghan M, Mente A, Zhang X, et al. Associations of fats and carbohydrate intake with cardiovascular disease and mortality in 18 countries from five continents (PURE): a prospective cohort study. *Lancet* 2017; **390**(10107): 2050-62.
113. Mensink RP, Katan MB. Effect of dietary fatty acids on serum lipids and lipoproteins: a meta-analysis of 27 trials. *Arteriosclerosis and Thrombosis* 1992; **12**: 911-9.
114. Jeppesen J, Schaaf P, Jones G, Zhou MY, Chen YD, Reaven GM. Effects of low-fat, high-carbohydrate diets on risk factors for ischemic heart disease in postmenopausal women. *Am J Clin Nutr* 1997; **65**: 1027-33.
115. Liu S, Willett WC, Stampfer MJ, et al. A prospective study of dietary glycemic load, carbohydrate intake, and risk of coronary heart disease in US women. *Am J Clin Nutr* 2000; **71**: 1455-61.
116. Willett WC, Stampfer M, Chu N, Spiegelman D, Holmes M, Rimm E. Assessment of questionnaire validity for measuring total fat intake using plasma lipid levels as criteria. *Am J Epidemiol* 2001; **154**: 1107-12.
117. Muraki I, Rimm EB, Willett WC, Manson JE, Hu FB, Sun Q. Potato Consumption and Risk of Type 2 Diabetes: Results From Three Prospective Cohort Studies. *Diabetes Care* 2016; **39**(3): 376-84.
118. Borgi L, Rimm EB, Willett WC, Forman JP. Potato intake and incidence of hypertension: results from three prospective US cohort studies. *BMJ* 2016; **353**: i2351.
119. Bertoia ML, Mukamal KJ, Cahill LE, et al. Changes in Intake of Fruits and Vegetables and Weight Change in United States Men and Women Followed for Up to 24 Years: Analysis from Three Prospective Cohort Studies. *PLoS Med* 2015; **12**(9): e1001878.

120. Wang X, Ouyang Y, Liu J, et al. Fruit and vegetable consumption and mortality from all causes, cardiovascular disease, and cancer: systematic review and dose-response meta-analysis of prospective cohort studies. *BMJ* 2014; **349**: g4490.
121. Aune D, Giovannucci E, Boffetta P, et al. Fruit and vegetable intake and the risk of cardiovascular disease, total cancer and all-cause mortality-a systematic review and dose-response meta-analysis of prospective studies. *Int J Epidemiol* 2016.
122. Binia A, Jaeger J, Hu Y, Singh A, Zimmermann D. Daily potassium intake and sodium-to-potassium ratio in the reduction of blood pressure: a meta-analysis of randomized controlled trials. *J Hypertens* 2015; **33**(8): 1509-20.
123. Muraki I, Imamura F, Manson JE, et al. Fruit consumption and risk of type 2 diabetes: results from three prospective longitudinal cohort studies. *BMJ* 2013; **347**: f5001.
124. Hung HC, Joshipura K, Jiang R, et al. Fruit and vegetable intake and the risk of major chronic disease. *J Natl Cancer Inst* 2004; **21**(21): 1577-84.
125. Boffetta P, Wichmann J, Ferrari P, et al. Fruit and vegetable intake and overall cancer risk in the European Prospective Investigation into Cancer and Nutrition (EPIC). *J Natl Cancer Inst* 2010; **102**(8): 529-37.
126. Wang DD, Li Y, Chiuve SE, et al. Association of Specific Dietary Fats With Total and Cause-Specific Mortality. *JAMA Intern Med* 2016.
127. Prentice RL, Caan B, Chlebowski RT, et al. Low-fat dietary pattern and risk of invasive breast cancer: the Women's Health Initiative Randomized Controlled Dietary Modification Trial. *Jama* 2006; **295**(6): 629-42.
128. Jakobsen MU, Dethlefsen C, Joensen AM, et al. Intake of carbohydrates compared with intake of saturated fatty acids and risk of myocardial infarction: importance of the glycemic index. *Am J Clin Nutr* 2010; **91**(6): 1764-8.
129. Farvid MS, Ding M, Pan A, et al. Dietary linoleic acid and risk of coronary heart disease: a systematic review and meta-analysis of prospective cohort studies. *Circulation* 2014; **130**(18): 1568-78.
130. Chowdhury R, Warnakula S, Kunutsor S, et al. Association of dietary, circulating, and supplement fatty acids with coronary risk: a systematic review and meta-analysis. *Ann Intern Med* 2014; **160**(6): 398-406.
131. Sacks F. Dietary fats and coronary heart disease. *Journal of Cardiovascular Risk* 1994; **1**: 3-41.
132. Mozaffarian D, Katan MB, Ascherio A, Stampfer MJ, Willett WC. Trans fatty acids and cardiovascular disease. *N Engl J Med* 2006; **354**(15): 1601-13.
133. Sun Y, Neelakantan N, Wu Y, Lote-Oke R, Pan A, van Dam RM. Palm Oil Consumption Increases LDL Cholesterol Compared with Vegetable Oils Low in Saturated Fat in a Meta-Analysis of Clinical Trials. *The Journal of nutrition* 2015; **145**(7): 1549-58.
134. Kabagambe EK, Baylin A, Ascherio A, Campos H. The type of oil used for cooking is associated with the risk of nonfatal acute myocardial infarction in costa rica. *The Journal of nutrition* 2005; **135**(11): 2674-9.
135. de Lorgeril M, Renaud S, Mamelle N, et al. Mediterranean alpha-linolenic acid-rich diet in secondary prevention of coronary heart disease [Erratum in: *Lancet* 1995;345:738]. *Lancet* 1994; **343**: 1454-9.
136. Puska P, Stahl T. Health in all policies-the Finnish initiative: background, principles, and current issues. *Annu Rev Public Health* 2010; **31**: 315-28 3 p following 28.
137. Chen M, Li Y, Sun Q, et al. Dairy fat and risk of cardiovascular disease in 3 cohorts of US adults. *Am J Clin Nutr* 2016; **104**(5): 1209-17.
138. Bray GA, Popkin BM. Dietary fat intake does affect obesity! *Am J Clin Nutr* 1998; **68**: 1157-73.
139. Hooper L, Abdelhamid A, Bunn D, Brown T, Summerbell CD, Skeaff CM. Effects of total fat intake on body weight. *Cochrane Database Syst Rev* 2015; (8): CD011834.

140. Knopp RH, Walden CE, Retzlaff BM, et al. Long-term cholesterol-lowering effects of 4 fat-restricted diets in hypercholesterolemic and combined hyperlipidemic men: The Dietary Alternatives Study. *J Am Med Assoc* 1997; **278**: 1509-15.
141. Tobias DK, Chen M, Manson JE, Ludwig DS, Willett W, Hu FB. Effect of low-fat diet interventions versus other diet interventions on long-term weight change in adults: a systematic review and meta-analysis. *Lancet Diabetes Endocrinol* 2015; **3**(12): 968-79.
142. Chiavaroli L, de Souza RJ, Ha V, et al. Effect of Fructose on Established Lipid Targets: A Systematic Review and Meta-Analysis of Controlled Feeding Trials. *J Am Heart Assoc* 2015; **4**(9): e001700.
143. Barclay AW, Petocz P, McMillan-Price J, et al. Glycemic index, glycemic load, and chronic disease risk--a meta-analysis of observational studies. *Am J Clin Nutr* 2008; **87**(3): 627-37.
144. Te Morenga L, Mallard S, Mann J. Dietary sugars and body weight: systematic review and meta-analyses of randomised controlled trials and cohort studies. *BMJ* 2012; **346**: e7492.
145. Malik VS, Popkin BM, Bray GA, Despres JP, Willett WC, Hu FB. Sugar-sweetened beverages and risk of metabolic syndrome and type 2 diabetes: a meta-analysis. *Diabetes Care* 2010; **33**(11): 2477-83.
146. Yang Q, Zhang Z, Gregg EW, Flanders WD, Merritt R, Hu FB. Added sugar intake and cardiovascular diseases mortality among US adults. *JAMA Intern Med* 2014; **174**(4): 516-24.
147. WHO. Guideline: sugars intake for adults and children. Geneva: World Health Organization, 2015.
148. W.H.O., Horta BL, Victora CG. Long-term effects of breastfeeding: a systematic review. Geneva: World Health Organization, 2013.
149. (UNICEF) UNCF. Infant and Young Child Feeding: A Systematic Review. New York: UNICEF, 2012.
150. W.H.O. Indicators for assessing infant and young child feeding practices. Washington, D.C.: World Health Organization, 2008.
151. WHO. Guideline: daily iron supplementation. Geneva: World Health Organization, 2016.
152. Maslova E, Rytter D, Bech BH, et al. Maternal protein intake during pregnancy and offspring overweight 20 y later. *Am J Clin Nutr* 2014; **100**(4): 1139-48.
153. Brantsaeter AL, Olafsdottir AS, Forsum E, Olsen SF, Thorsdottir I. Does milk and dairy consumption during pregnancy influence fetal growth and infant birthweight? . *Food and Nutrition Research* 2012; **56**(20050).
154. Piccoli GB, Clari R, Vigotti FN, et al. Vegan-vegetarian diets in pregnancy: danger or panacea? A systematic narrative review. *BJOG* 2015; **122**(5): 623-33.
155. W.H.O. WHO recommendations for antenatal care for a positive pregnancy experience. Geneva: World Health Organization, 2016.
156. Sánchez PH, Ruano C, De Irala J, Ruiz-Canela M, Martinez-Gonzalez M, Sánchez-Villegas A. Adherence to the Mediterranean diet and quality of life in the SUN Project. *Eur J Clin Nutr* 2012; **66**(3): 360.
157. Bhushan A, Fondell E, Ascherio A, Yuan C, Grodstein F, Willett W. Adherence to Mediterranean diet and subjective cognitive function in men. *European journal of epidemiology* 2017: 1-12.
158. Morris MC, Tangney CC, Wang Y, Sacks FM, Bennett DA, Aggarwal NT. MIND diet associated with reduced incidence of Alzheimer's disease. *Alzheimer's & dementia: the journal of the Alzheimer's Association* 2015; **11**(9): 1007-14.
159. Appel LJ, Moore TJ, Obarzanek E, et al. A clinical trial of the effects of dietary patterns on blood pressure. DASH Collaborative Research Group. *N Engl J Med* 1997; **336**(16): 1117-24.
160. Sacks FM, Svetkey LP, Vollmer WM, et al. Effects on blood pressure of reduced dietary sodium and the dietary approaches to stop hypertension (DASH) diet. *N Engl J Med* 2001; **344**: 3-10.

161. Anand SS, Hawkes C, de Souza RJ, et al. Food Consumption and its Impact on Cardiovascular Disease: Importance of Solutions Focused on the Globalized Food System: A Report From the Workshop Convened by the World Heart Federation. *J Am Coll Cardiol* 2015; **66**(14): 1590-614.
162. Chiuve SE, Sampson L, Willett WC. The association between a nutritional quality index and risk of chronic disease. *Am J Prev Med* 2011; **40**(5): 505-13.
163. Cespedes EM, Hu FB, Tinker L, et al. Multiple Healthful Dietary Patterns and Type 2 Diabetes in the Women's Health Initiative. *Am J Epidemiol* 2016; **183**(7): 622-33.
164. Mehta RS, Song M, Nishihara R, et al. Dietary Patterns and Risk of Colorectal Cancer: Analysis by Tumor Location and Molecular Subtypes. *Gastroenterology* 2017.
165. Hou L, Li F, Wang Y, et al. Association between dietary patterns and coronary heart disease: a meta-analysis of prospective cohort studies. *Int J Clin Exp Med* 2015; **8**(1): 781-90.
166. Trichopoulou A, Costacou T, Bamia C, Trichopoulos D. Adherence to a Mediterranean diet and survival in a Greek population. *N Engl J Med* 2003; **348**: 2599-608.
167. Samieri C, Sun Q, Townsend MK, et al. The association between dietary patterns at midlife and health in aging: an observational study. *Ann Intern Med* 2013; **159**(9): 584-91.
168. Sotos-Prieto M, Bhupathiraju SN, Mattei J, et al. Association of Changes in Diet Quality with Total and Cause-Specific Mortality. *N Engl J Med* 2017; **377**(2): 143-53.
169. Micha R, Shulkin ML, Peñalvo JL, et al. Etiologic effects and optimal intakes of foods and nutrients for risk of cardiovascular diseases and diabetes: systematic reviews and meta-analyses from the Nutrition and Chronic Diseases Expert Group (NutriCoDE). *PloS one* 2017; **12**(4): e0175149.
170. Chaudhary A, Gustafson D, Mathys A. Multi-indicator sustainability assessment of global food systems. *Nature communications* 2018; **9**(1): 848.
171. Micha R, Michas G, Mozaffarian D. Unprocessed red and processed meats and risk of coronary artery disease and type 2 diabetes--an updated review of the evidence. *Curr Atheroscler Rep* 2012; **14**(6): 515-24.
172. Springmann M, Wiebe K, Mason-D'Croz D, Rayner M, Scarborough P. The health and environmental aspects of sustainable-diet strategies – a comparative global modelling analysis with country-level detail. *Lancet Planetary Health* In review.
173. GBD Diet Collaborators. Health effects of dietary risks in 195 countries: findings from the Global Burden of Diseases Study 2017. *Lancet* Under review.
174. Chiuve SE, Fung TT, Rimm EB, et al. Alternative Dietary Indices Both Strongly Predict Risk of Chronic Disease–. *The Journal of nutrition* 2012; **142**(6): 1009-18.
175. Wang DD, Li Y, Chiuve SE, Hu FB, Willett WC. Improvements in US diet helped reduce disease burden and lower premature deaths, 1999–2012; overall diet remains poor. *Health Affairs* 2015; **34**(11): 1916-22.
176. Schwingshackl L, Hoffmann G. Diet quality as assessed by the Healthy Eating Index, the Alternate Healthy Eating Index, the Dietary Approaches to Stop Hypertension score, and health outcomes: a systematic review and meta-analysis of cohort studies. *Journal of the Academy of Nutrition and Dietetics* 2015; **115**(5): 780-800. e5.
177. Onvani S, Haghighatdoost F, Surkan P, Larijani B, Azadbakht L. Adherence to the Healthy Eating Index and Alternative Healthy Eating Index dietary patterns and mortality from all causes, cardiovascular disease and cancer: a meta-analysis of observational studies. *Journal of Human Nutrition and Dietetics* 2017; **30**(2): 216-26.
178. DeClerck F, Jones S, Attwood S, et al. Agricultural ecosystems and their services: the vanguard of sustainability? *Current opinion in environmental sustainability* 2016; **23**: 92-9.
179. Garibaldi LA, Carvalheiro LG, Vaissière BE, et al. Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. *Science* 2016; **351**(6271): 388-91.

180. Garbach K, Milder JC, De Clerck F, Driscoll L, Montenegro M, Herren B. Close yield and nature gaps: Multi-functionality in five systems of agroecological intensification. *International Journal of Agricultural Sustainability* 2016.
181. Garnett T, Appleby MC, Balmford A, et al. Sustainable Intensification in Agriculture: Premises and Policies. *Science* 2013; **341**(6141): 33-4.
182. Tilman D, Balzer C, Hill J, Befort BL. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America* 2011; **108**(50): 20260-4.
183. Rockström J, Williams J, Daily G, et al. Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio* 2017; **46**(1): 4-17.
184. Steffen W, Crutzen PJ, McNeill JR. The Anthropocene: Are humans now overwhelming the great forces of nature. *Ambio* 2007; **36**(8): 614-21.
185. Lambin EF, Meyfroidt P. Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences* 2011; **108**(9): 3465-72.
186. Keys PW, Wang-Erlandsson L, Gordon LJ. Revealing invisible water: moisture recycling as an ecosystem service. *PloS one* 2016; **11**(3): e0151993.
187. Bahn M, Reichstein M, Dukes JS, Smith MD, McDowell NG. Climate–biosphere interactions in a more extreme world. *New Phytologist* 2014; **202**(2): 356-9.
188. Galaz V, Biermann F, Folke C, Nilsson M, Olsson P. Global environmental governance and planetary boundaries: An introduction. *Ecol Econ* 2012; **81**: 1-3.
189. Brondizio ES, O'brien K, Bai X, et al. Re-conceptualizing the Anthropocene: A call for collaboration. *Global Environmental Change* 2016; **39**: 318-27.
190. Steffen W, Richardson K, Rockstrom J, et al. Planetary boundaries: Guiding human development on a changing planet. *Science* 2015; **347**(6223): 347-57.
191. Campbell B, Beare D, Bennett E, et al. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society* 2017; **22**(4).
192. Conijn J, Bindraban P, Schröder J, Jongschaap R. Can our global food system meet food demand within planetary boundaries? *Agriculture, Ecosystems & Environment* 2018; **251**: 244-56.
193. Newbold T, Hudson LN, Arnell AP, et al. Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science* 2016; **353**(6296): 288-91.
194. Rockstrom J, Steffen W, Noone K, et al. A safe operating space for humanity. *Nature* 2009; **461**(7263): 472-5.
195. IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. , 2014.
196. Obersteiner M, Bednar J, Wagner F, et al. How to spend a dwindling greenhouse gas budget. *Nature Climate Change* 2018; **8**(1): 7.
197. Smith P, Clark H, Dong H, et al. Agriculture, forestry and other land use (AFOLU). 2014.
198. Vermeulen SJ, Campbell BM, Ingram JSI. Climate Change and Food Systems. In: Gadgil A, Liverman DM, eds. Annual Review of Environment and Resources, Vol 37; 2012: 195-+.
199. Bennetzen EH, Smith P, Porter JR. Decoupling of greenhouse gas emissions from global agricultural production: 1970–2050. *Glob Change Biol* 2016; **22**(2): 763-81.
200. Wollenberg E, Richards M, Smith P, et al. Reducing emissions from agriculture to meet the 2 C target. *Global Change Biol* 2016; **22**(12): 3859-64.
201. Van Vuuren DP, Edmonds J, Kainuma M, et al. The representative concentration pathways: an overview. *Climatic Change* 2011; **109**(1-2): 5.
202. Van Vuuren DP, Stehfest E, den Elzen MG, et al. RCP2. 6: exploring the possibility to keep global mean temperature increase below 2 C. *Climatic Change* 2011; **109**(1-2): 95.
203. HLPE. Water for food security and nutrition. Rome: FAO, 2015.

204. Wada Y, Van Beek L, Bierkens MF. Modelling global water stress of the recent past: on the relative importance of trends in water demand and climate variability. *Hydrology and Earth System Sciences* 2011; **15**(12): 3785-805.
205. Falkenmark M, Rockström J. The new blue and green water paradigm: Breaking new ground for water resources planning and management. American Society of Civil Engineers; 2006.
206. Keys PW, Van der Ent R, Gordon LJ, Hoff H, Nikoli R, Savenije H. Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences* 2012; **9**(2): 733-46.
207. Declaration B. The Brisbane Declaration: environmental flows are essential for freshwater ecosystem health and human well-being. 10th International River Symposium, Brisbane, Australia; 2007; 2007. p. 3-6.
208. Shiklomanov I, Rodda J. World Water Resources at the Beginning of the 21st Cen. 2003.
209. Pastor A, Ludwig F, Biemans H, Hoff H, Kabat P. Accounting for environmental flow requirements in global water assessments. *Hydrology and Earth System Sciences* 2014; **18**(12): 5041-59.
210. Jaramillo F, Destouni G. Local flow regulation and irrigation raise global human water consumption and footprint. *Science* 2015; **350**(6265): 1248-51.
211. Molden D. Planetary boundaries: The devil is in the detail. *Nature reports climate change* 2009: 116-7.
212. Gerten D, Hoff H, Rockström J, Jägermeyr J, Kummu M, Pastor AV. Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. *Curr Opin Env Sust* 2013; **5**(6): 551-8.
213. Rosegrant MW, Ringler C, Zhu T. Water for agriculture: maintaining food security under growing scarcity. *Annual review of Environment and resources* 2009; **34**.
214. Fader M, Gerten D, Krause M, Lucht W, Cramer W. Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. *Environmental Research Letters* 2013; **8**(1): 014046.
215. De Marsily G, Abarca-del-Rio R. Water and food in the twenty-first century. *Surveys in Geophysics* 2016; **37**(2): 503-27.
216. Rockström J, Folke C, Gordon L, et al. A watershed approach to upgrade rainfed agriculture in water scarce regions through Water System Innovations: an integrated research initiative on water for food and rural livelihoods in balance with ecosystem functions. *Physics and Chemistry of the Earth, Parts A/B/C* 2004; **29**(15-18): 1109-18.
217. Zimmer MA, Bailey SW, McGuire KJ, Bullen TD. Fine scale variations of surface water chemistry in an ephemeral to perennial drainage network. *Hydrological Processes* 2013; **27**(24): 3438-51.
218. Cai X, Rosegrant MW. 10 World Water Productivity: Current Situation and Future Options. *Water productivity in agriculture: limits and opportunities for improvement* 2003; **1**: 163.
219. Jägermeyr J, Gerten D, Heinke J, Schaphoff S, Kummu M, Lucht W. Water savings potentials of irrigation systems: global simulation of processes and linkages. *Hydrology and Earth System Sciences* 2015; **19**(7): 3073.
220. Eickhout B, Bouwman AF, van Zeijts H. The role of nitrogen in world food production and environmental sustainability. *Agric Ecosyst Environ* 2006; **116**(1-2): 4-14.
221. Erisman JW, Sutton MA, Galloway J, Klimont Z, Winiwarter W. How a century of ammonia synthesis changed the world. *Nat Geosci* 2008; **1**(10): 636-9.
222. Robertson GP, Vitousek PM. Nitrogen in Agriculture: Balancing the Cost of an Essential Resource. *Annual Review of Environment and Resources* 2009; **34**(1): 97-125.
223. Sutton MA, Bleeker A, Howard CM, et al. Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. Nairobi: Centre for Ecology and Hydrology, Edinburgh & United Nations Environment Programme; 2013.

224. Seitzinger SP, Kroeze C, Bouwman AF, Caraco N, Dentener F, Styles RV. Global patterns of dissolved inorganic and particulate nitrogen inputs to coastal systems: recent conditions and future projections. *Estuaries* 2002; **25**(4): 640-55.
225. Strokal M, Kroeze C, Wang M, Bai Z, Ma L. The MARINA model (Model to Assess River Inputs of Nutrients to seAs): model description and results for China. *Science of the Total Environment* 2016; **562**: 869-88.
226. Clark CM, Tilman D. Loss of plant species after chronic low-level nitrogen deposition to prairie grasslands. *Nature* 2008; **451**(7179): 712.
227. Bobbink R, Hicks K, Galloway J, et al. Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. *Ecological applications* 2010; **20**(1): 30-59.
228. Bleeker A, Hicks W, Dentener F, Galloway J, Erisman J. N deposition as a threat to the World's protected areas under the Convention on Biological Diversity. *Environmental pollution* 2011; **159**(10): 2280-8.
229. Guo JH, Liu XJ, Zhang Y, et al. Significant acidification in major Chinese croplands. *Science* 2010; **327**(5968): 1008-10.
230. Velthof GL, Barot S, Bloem J, et al. Nitrogen as a threat to European soil quality. In: Sutton MA, Howard CM, Erisman JW, et al., eds. The European Nitrogen Assessment. Cambridge, UK: Cambridge University Press, Chapter 21; 2011: 494-509.
231. Syakila A, Kroeze C. The global nitrous oxide budget revisited. *Greenhouse Gas Measurement & Management* 2011; **1**(1): 17-26.
232. EEA. The European environment – State and outlook 2005. Copenhagen: European Environment Agency; 2005.
233. UNEP, United Nations Environment Programme. Global Environmental Outlook 4. (GEO-4) United Nations Environment Program. Nairobi, Kenya; 2007.
234. Lelieveld J, Evans JS, Fnais M, Giannadaki D, Pozzer A. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* 2015; **525**(7569): 367.
235. WHO. Global Health Observatory Map Gallery: http://www.who.int/. 2011.
236. Erisman JW, Galloway JN, Seitzinger S, et al. Consequences of human modification of the global nitrogen cycle. *Phil Trans R Soc Lond B* 2013; **(in press)**.
237. Van Dingenen R, Dentener FJ, Raes F, Krol MC, Emberson L, Cofala J. The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmos Environ* 2009; **43**: 604-18.
238. Shindell D, Kuylenstierna JCI, Vignati E, et al. Simultaneously mitigating near-term climate change and improving human health and food security. *Science* 2012; **335**(6065): 183-9.
239. Cordell D, Drangert J-O, White S. The story of phosphorus: global food security and food for thought. *Global environmental change* 2009; **19**(2): 292-305.
240. Nordhaus T, Shellenberger M, Blomqvist L. The planetary boundaries hypothesis a review of the evidence. Oakland, Ca.: Breakthrough Institute; 2012.
241. De Vries W, Kros J, Kroeze C, Seitzinger SP. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. *Curr Opin Env Sust* 2013; **5**(3-4): 392-402.
242. Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA. Closing yield gaps through nutrient and water management. *Nature* 2012; **490**: 254-7.
243. Vitousek PM, Naylor R, Crews T, et al. Nutrient imbalances in agricultural development. *Science* 2009; **324**: 1519-20.
244. Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA. Closing yield gaps through nutrient and water management. *Nature* 2012; **490**(7419): 254.
245. Vitousek PM, Naylor R, Crews T, et al. Nutrient imbalances in agricultural development. *Science* 2009; **324**(5934): 1519-20.
246. Heffer P. Assessment of Fertilizer Use by Crop at the Global Level 2010-2010/11. International Fertilizer Industry Association, Paris. 2013.

247. Lassaletta L, Billen G, Grizzetti B, Anglade J, Garnier J. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environmental Research Letters* 2014; **9**(10): 105011.
248. Carpenter SR, Bennett EM. Reconsideration of the planetary boundary for phosphorus. *Environmental Research Letters* 2011; **6**(1).
249. De Vries W. Planetary boundary for phosphorus. In supplementary material of Springmann et al. 'Changes in food management, technology and diets to stay within planetary boundaries'. *Nature*; **Submitted**.
250. Cardinale BJ, Duffy JE, Gonzalez A, et al. Biodiversity loss and its impact on humanity. *Nature* 2012; **486**(7401): 59.
251. Tilman D, Isbell F, Cowles JM. Biodiversity and ecosystem functioning. *Annual review of ecology, evolution, and systematics* 2014; **45**.
252. Naeem S, Duffy JE, Zavaleta E. The Functions of Biological Diversity in an Age of Extinction. *Science* 2012; **336**(6087): 1401-6.
253. Cardinale BJ. Biodiversity improves water quality through niche partitioning. *Nature* 2011; **472**: 86-90.
254. Sala OE, Chapin FS, Armesto JJ, et al. Global biodiversity scenarios for the year 2100. *science* 2000; **287**(5459): 1770-4.
255. Hooper DU, Adair EC, Cardinale BJ, et al. A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature* 2012; **486**(7401): 105.
256. Costanza R, dArge R, deGroot R, et al. The value of the world's ecosystem services and natural capital. *Nature* 1997; **387**(6630): 253-60.
257. Silvertown J. Dinner with Darwin: Food, Drink, and Evolution: University of Chicago Press; 2017.
258. Barnosky AD, Hadly EA, Bascompte J, et al. - Approaching a state shift in Earth/'s biosphere. 2012; **- 486**(- 7401): - 58.
259. Ceballos G, Ehrlich PR, Dirzo R. Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. *Proceedings of the National Academy of Sciences* 2017; **114**(30): E6089-E96.
260. Pimm SL, Jenkins CN, Abell R, et al. The biodiversity of species and their rates of extinction, distribution, and protection. *Science* 2014; **344**(6187): 1246752.
261. Butchart SHM, Walpole M, Collen B, et al. Global Biodiversity: Indicators of Recent Declines. *Science* 2010; **328**(5982): 1164-8.
262. Tilman D, Fargione J, Wolff B, et al. Forecasting agriculturally driven global environmental change. *Science* 2001; **292**(5515): 281-4.
263. Tilman D, Clark M, Williams DR, Kimmel K, Polasky S, Packer C. Future threats to biodiversity and pathways to their prevention. *Nature* 2017; **546**(7656): 73.
264. Phalan B, Onial M, Balmford A, Green RE. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. *Science* 2011; **333**(6047): 1289-91.
265. Barnosky AD, Matzke N, Tomiya S, et al. Has the Earth's sixth mass extinction already arrived? *Nature* 2011; **471**(7336): 51.
266. Ehrlich P, Walker B. Rivets and redundancy. *Bioscience* 1998; **48**(5): 387-.
267. Hallmann CA, Sorg M, Jongejans E, et al. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PloS one* 2017; **12**(10): e0185809.
268. Thompson K. De we need pandas? : the uncomfortable truth about biodiversity. London: Little Green; 2010.
269. Chaudhary A, Kastner T. Land use biodiversity impacts embodied in international food trade. *Global Environmental Change-Human and Policy Dimensions* 2016; **38**: 195-204.
270. Chaudhary A, Pfister S, Hellweg S. Spatially Explicit Analysis of Biodiversity Loss Due to Global Agriculture, Pasture and Forest Land Use from a Producer and Consumer Perspective. *Environmental Science & Technology* 2016; **50**(7): 3928-36.

271. Chaudhary A, Verones F, de Baan L, Hellweg S. Quantifying Land Use Impacts on Biodiversity: Combining Species-Area Models and Vulnerability Indicators. *Environmental Science & Technology* 2015; **49**(16): 9987-95.
272. Harris NL, Brown S, Hagen SC, et al. Baseline map of carbon emissions from deforestation in tropical regions. *Science* 2012; **336**(6088): 1573-6.
273. Ramankutty N, Evan AT, Monfreda C, Foley JA. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles* 2008; **22**(1).
274. Dinerstein E, Olson D, Joshi A, et al. An ecoregion-based approach to protecting half the terrestrial realm. *BioScience* 2017; **67**(6): 534-45.
275. Eken G, Bennun L, Brooks TM, et al. Key biodiversity areas as site conservation targets. *Bioscience* 2004; **54**(12): 1110-8.
276. Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J. Biodiversity hotspots for conservation priorities. *Nature* 2000; **403**(6772): 853-8.
277. Griscom BW, Adams J, Ellis PW, et al. Natural climate solutions. *Proceedings of the National Academy of Sciences* 2017; **114**(44): 11645-50.
278. Wilson EO. Half Earth: Our Planet's Fight for Life. New York: Liveright Publishing Corporation; 2016.
279. Tscharntke T, Klein AM, Kruess A, Steffan-Dewenter I, Thies C. Landscape perspectives on agricultural intensification and biodiversity - ecosystem service management. *Ecology Letters* 2005; **8**(8): 857-74.
280. Jantz P, Goetz S, Laporte N. Carbon stock corridors to mitigate climate change and promote biodiversity in the tropics. *Nature Climate Change* 2014; **4**(2): 138.
281. Karp DS, Frishkoff LO, Echeverri A, Zook J, Juárez P, Chan KM. Agriculture erases climate-driven β-diversity in Neotropical bird communities. *Global Change Biol* 2018; **24**(1): 338-49.
282. Mitsch WJ, Day Jr JW, Gilliam JW, et al. Reducing Nitrogen Loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to Counter a Persistent Ecological Problem: Ecotechnology—the use of natural ecosystems to solve environmental problems—should be a part of efforts to shrink the zone of hypoxia in the Gulf of Mexico. *Bioscience* 2001; **51**(5): 373-88.
283. Clune S, Crossin E, Verghese K. Systematic review of greenhouse gas emissions for different fresh food categories. *Journal of Cleaner Production* 2017; **140, Part 2**: 766-83.
284. Davis KF, Gephart JA, Emery KA, Leach AM, Galloway JN, D'Odorico P. Meeting future food demand with current agricultural resources. *Global Environmental Change* 2016; **39**: 125-32.
285. Nelson ME, Hamm MW, Hu FB, Abrams SA, Griffin TS. Alignment of Healthy Dietary Patterns and Environmental Sustainability: A Systematic Review. *Advances in Nutrition: An International Review Journal* 2016; **7**(6): 1005-25.
286. Aleksandrowicz L, Green R, Joy EJ, Smith P, Haines A. The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. *PloS one* 2016; **11**(11): e0165797.
287. Hallström E, Carlsson-Kanyama A, Börjesson P. Environmental impact of dietary change: a systematic review. *Journal of Cleaner Production* 2015; **91**: 1-11.
288. Peters CJ, Picardy J, Darrouzet-Nardi AF, Wilkins JL, Griffin TS, Fick GW. Carrying capacity of US agricultural land: Ten diet scenarios. *Elem Sci Anth* 2016; **4**.
289. Tilman D, Balzer C, Hill J, Befort BL. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences* 2011; **108**(50): 20260-4.
290. Smith P, Bustamante M, Ahammad H, et al. Agriculture, Forestry and Other Land Use (AFOLU). In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., eds. Climate Change 2014:

Mitigation of Climate Change Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and NY, USA: Cambridge University Press; 2014: 811-922.
291. Springmann M, Clark M, D'Croz D, et al. Changes in food management, technology and diets to stay within planetary boundaries. *Nature* Forthcoming.
292. Robinson S, Mason-D'Croz D, Sulser T, et al. The international model for policy analysis of agricultural commodities and trade (IMPACT): model description for version 3. 2015.
293. Carlson KM, Gerber JS, Mueller ND, et al. Greenhouse gas emissions intensity of global croplands. *Nature Climate Change* 2017; **7**(1): 63.
294. Tubiello FN, Salvatore M, Rossi S, Ferrara A, Fitton N, Smith P. The FAOSTAT database of greenhouse gas emissions from agriculture. *Environmental Research Letters* 2013; **8**(1): 015009.
295. Heffer P. Assessment of Fertilizer Use by Crop at the Global Level 2010–2010/11, 2013.
296. Alexandratos N, Bruinsma J. World agriculture towards 2030/2050: the 2012 revision. Rome: FAO, 2012.
297. Interagency Working Group. Technical update on the social cost of carbon for regulatory impact analysis-under executive order 12866: United States Government, 2013.
298. Beach RH, Creason J, Ohrel SB, et al. Global mitigation potential and costs of reducing agricultural non-CO2 greenhouse gas emissions through 2030. *Journal of Integrative Environmental Sciences* 2015; **12**(sup1): 87-105.
299. Sutton MA, Bleeker A, Howard C, et al. Our nutrient world: the challenge to produce more food and energy with less pollution: NERC/Centre for Ecology & Hydrology; 2013.
300. Cordell D, White S. Life's bottleneck: sustaining the world's phosphorus for a food secure future. *Annual Review of Environment and Resources* 2014; **39**: 161-88.
301. Herrero M, Henderson B, Havlík P, et al. Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change* 2016; **6**(5): 452.
302. Hedenus F, Wirsenius S, Johansson DJ. The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Climatic change* 2014; **124**(1-2): 79-91.
303. Bajželj B, Richards KS, Allwood JM, et al. Importance of food-demand management for climate mitigation. *Nature Climate Change* 2014; **4**(10): 924-9.
304. Popp A, Lotze-Campen H, Bodirsky B. Food consumption, diet shifts and associated non-CO 2 greenhouse gases from agricultural production. *Global Environmental Change* 2010; **20**(3): 451-62.
305. Erb K-H, Lauk C, Kastner T, Mayer A, Theurl MC, Haberl H. Exploring the biophysical option space for feeding the world without deforestation. *Nature Communications* 2016; **7**: 11382.
306. Ray DK, Mueller ND, West PC, Foley JA. Yield trends are insufficient to double global crop production by 2050. *PloS one* 2013; **8**(6): e66428.
307. Evenson RE, Gollin D. Assessing the impact of the green revolution, 1960 to 2000. *Science* 2003; **300**(5620): 758-62.
308. Pingali PL. Green Revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences* 2012; **109**(31): 12302-8.
309. Jägermeyr J, Gerten D, Heinke J, Schaphoff S, Kummu M, Lucht W. Water savings potentials of irrigation systems: global simulation of processes and linkages. *Hydrol Earth Syst Sci* 2015; **19**(7): 3073-91.
310. Rosegrant MW, Cai X, Cline SA. World water and food to 2025. Washington, DC: IFPRI, 2002.
311. Jalava M, Kummu M, Porkka M, Siebert S, Varis O. Diet change—a solution to reduce water use? *Environmental research letters* 2014; **9**(7): 074016.
312. Zhang X, Davidson EA, Mauzerall DL, Searchinger TD, Dumas P, Shen Y. Managing nitrogen for sustainable development. *Nature* 2015; **528**(7580): 51.

313. Lassaletta L, Billen G, Garnier J, et al. Nitrogen use in the global food system: past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand. *Environmental Research Letters* 2016; **11**(9): 095007.
314. Bouwman L, Goldewijk KK, Van Der Hoek KW, et al. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period. *P Natl Acad Sci USA* 2013; **110**(52): 20882-7.
315. Bodirsky BL, Popp A, Lotze-Campen H, et al. Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nature communications* 2014; **5**.
316. MacDonald GK, Bennett EM, Potter PA, Ramankutty N. Agronomic phosphorus imbalances across the world's croplands. *Proceedings of the National Academy of Sciences* 2011; **108**(7): 3086-91.
317. Ceballos G, Ehrlich PR, Barnosky AD, García A, Pringle RM, Palmer TM. Accelerated modern human–induced species losses: Entering the sixth mass extinction. *Science advances* 2015; **1**(5): e1400253.
318. Eken G, Bennun L, Brooks TM, et al. Key Biodiversity Areas as Site Conservation Targets. *BioScience* 2004; **54**(12): 1110-8.
319. Butchart SH, Clarke M, Smith RJ, et al. Shortfalls and solutions for meeting national and global conservation area targets. *Conservation Letters* 2015; **8**(5): 329-37.
320. Balmford A, Moore JL, Brooks T, et al. Conservation conflicts across Africa. *Science* 2001; **291**(5513): 2616-9.
321. Ricketts TH, Dinerstein E, Boucher T, et al. Pinpointing and preventing imminent extinctions. *P Natl Acad Sci USA* 2005; **102**(51): 18497-501.
322. Chaudhary A, Kastner T. Land use biodiversity impacts embodied in international food trade. *Global Environmental Change* 2016; **38**: 195-204.
323. Chaudhary A, Brooks TM. National Consumption and Global Trade Impacts on Biodiversity. *World Development* 2017.
324. Chaudhary A, Burivalova Z, Koh LP, Hellweg S. Impact of forest management on species richness: global meta-analysis and economic trade-offs. *Scientific reports* 2016; **6**: 23954.
325. Demeyer D, Honikel K, De Smet S. The World Cancer Research Fund report 2007: A challenge for the meat processing industry. *Meat science* 2008; **80**(4): 953-9.
326. WHO. Human energy requirements: Report of a Joint FAO/WHO/UNU expert consultation, Rome, Italy, 17-24 October 2001. Geneva: World Health Organization, 2004.
327. WEF. Innovation with a purpose: the role of technology innovation in accelerating food systems transformations: World Economic Forum, McKinsey & Company, 2018.
328. Van Huis A. Potential of insects as food and feed in assuring food security. *Annual Review of Entomology* 2013; **58**: 563-83.
329. Alexander P, Brown C, Arneth A, et al. Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Global Food Security* 2017.
330. IAASTD. Agriculture at a crossroads: global report. Washington, DC, 2008.
331. UNEP, Nellemann C, MacDevette M, et al. The Environmental Food Crisis: The Environment's role in averting future food crises. A UNEP rapid response assessment. Arendal, Norway: United Nations Environment Programme / GRID-Arendal 2009.
332. Paillard S, Treyer S, Dorin B, editors. Agrimonde: Scenarios and Challenges for Feeding the World in 2050. Paris: Editions Quae; 2010.
333. Foresight. The Future of Food and Farming: Challenges and choices for global sustainability. London: Government Office for Science, 2011.
334. Fanzo JC, Cogill B, Mattei F. Metrics of Sustainable Diets and Food Systems. Rome: Bioversity International, 2012.
335. UNEP. Avoiding Future Famines: Strengthening the Ecological Basis of Food Security through Sustainable Food Systems. Nairobi: United Nations Environment Programme, 2012.

336. FAO. The state of food and agriculture: food systems for better nutrition. Rome: Food and Agriculture Organization, 2013.
337. Global Panel on Agriculture and Food Systems for Nutrition. How can Agriculture and Food System Policies improve Nutrition? Technical Brief. London, UK: Global Panel on Agriculture and Food Systems for Nutrition, 2014.
338. iPES Food. The new science of sustainable food systems: overcoming barriers to food systems reform: International Panel of Experts on Sustainable Food Systems, 2015.
339. Townsend R. Ending poverty and hunger by 2030: an agenda for the global food system. Washington, DC: World Bank Group, 2015.
340. HLPE. Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome, 2017.
341. Walker B, Holling CS, Carpenter S, Kinzig A. Resilience, adaptability and transformability in social–ecological systems. *Ecology and society* 2004; **9**(2).
342. IFPRI. Food system transformations: Brazil, Rwanda, and Vietnam: IFRI, Compact 2025 Initiative, 2016.
343. Garnett T, Wilkes A. Appetite for change: social, economic and environmental transformations in China's food system. Oxford, UK: FCRN, 2014.
344. Puska P, Nissinen A, Tuomilehto J, et al. The community-based strategy to prevent coronary heart disease: conclusions from the ten years of the North Karelia project. *Annual review of public health* 1985; **6**(1): 147-93.
345. Popkin BM, Hawkes C. Sweetening of the global diet, particularly beverages: patterns, trends, and policy responses. *The Lancet Diabetes & Endocrinology* 2016; **4**(2): 174-86.
346. Hot Springs Conference. Final Act of the Hot Springs Conference, 18 May - 3 June 1943 - http://www.fao.org/docrep/009/p4228e/P4228E04.htm. Hot Springs Virginia USA, 1943.
347. Brandt K. The Reconstruction of World Agriculture. London: George Allen & Unwin; 1945.
348. Schubert SD, Suarez MJ, Pegion PJ, Koster RD, Bacmeister JT. On the cause of the 1930s Dust Bowl. *Science* 2004; **303**(5665): 1855-9.
349. Worster D. Dust bowl: the southern plains in the 1930s: Oxford University Press; 2004.
350. Conquest R. The harvest of sorrow: Soviet collectivization and the terror-famine: Oxford University Press, USA; 1987.
351. Dreze J, Sen A. Hunger and public action: Oxford University Press on Demand; 1989.
352. Fogel RW. The escape from hunger and premature death, 1700-2100: Europe, America, and the Third World: Cambridge University Press; 2004.
353. Boyd Orr J. Food, health and income: report on adequacy of diet in relation to income. London: Macmillan & Co, 1936.
354. Morgan K, Sonnino R. The School Food Revolution: Public Food and the Challenge of Sustainable Development. London: Earthscan; 2008.
355. WHO. Global Health Observatory data: HIV Aids. 2018. http://www.who.int/gho/hiv/en/
356. WHO. MPower strategy. 2014. http://www.who.int/tobacco/mpower/en/
357. WHO. WHO plan to eliminate industrially-produced trans-fatty acids from global food supply. Geneva: World Health Organization; 2018.
358. Johnston PV, Johnson OC, Kummerow FA. Occurrence of trans fatty acids in human tissue. *Science* 1957; **126**(3276): 698-9.
359. Willett WC, Stampfer MJ, Manson JE, et al. Intake of trans fatty acids and risk of coronary heart disease among women. *The Lancet* 1993; **341**(8845): 581-5.
360. IPCC. Climate Change 2014 Synthesis Report - Summary for Policymakers. Geneva: Intergovernmental Panel on Climate Change, 2014.
361. OECD. World Energy Outlook 2017. Paris: Organization for Economic Cooperation and Development, 2017.
362. EEA. Eutrophication. Copenhagen: European Environment Agency, 2016.

363. Eurostat. Agri-environmental indicator - mineral fertiliser consumption. Brussels: European Commission, 2017.
364. European Commission. Science for environment policy. Bristol: European Commission DG Environment News Alert Service, 2014.
365. Nuffield Council on Bioethics. Public health: ethical issues. Cambridge UK: Cambridge Publishers / Nuffield Council on Bioethics. http://nuffieldbioethics.org/project/public-health/, 2007.
366. Lang T, Mason P. Sustainable diets: a bundle of policy problems in search of answers. In: Burlingame B, Dernini S, eds. Sustainable diets: transdisciplinary imperative. Wallingford: CABI; 2018.
367. Mozaffarian D, Angell SY, Lang T, Rivera JA. Role of government policy in nutrition—barriers to and opportunities for healthier eating. *BMJ* 2018; **361**: k2426.
368. FAO. Strategic work of FAO for sustainable food and agriculture. Rome: FAO, 2017.
369. Stuckler D, Nestle M. Big food, food systems, and global health. *PLoS medicine* 2012; **9**(6): e1001242.
370. IPES-Food. Unravelling the Food-Health Nexus: Addressing Practices, Political Economy, and Power Relations to Build Healthier Food Systems: International Panel of Experts on Food (IPES-Food) & the Global Alliance for Future of Food, 2017.
371. Lang T, Heasman M. Food Wars: the global battle for mouths, minds and markets. 2nd edition. 2nd ed. Abingdon: Routledge Earthscan; 2015.
372. Rockefeller Foundation, USAID, SIDA. Global Resilience Partnership and 100 Cities project. New York: Rockefeller Foundation, US Agency for International Development (USAID), and Swedish International Development Co-operation Agency (SIDA), 2018.
373. Sisnowski J, Street JM, Merlin T. Improving food environments and tackling obesity: A realist systematic review of the policy success of regulatory interventions targeting population nutrition. *PloS one* 2017; **12**(8): e0182581.
374. Smith J, Andersson G, Gourlay R, et al. Balancing competing policy demands: the case of sustainable public sector food procurement. *Journal of Cleaner Production* 2016; **112**(Part 1): 249-56.
375. Rivera JA, Shamah T, Villalpando S, Monterrubio E. Effectiveness of a large-scale iron-fortified milk distribution program on anemia and iron deficiency in low-income young children in Mexico. *Am J Clin Nutr* 2009; **91**(2): 431-9.
376. Sturm R, Hattori A. Diet and obesity in Los Angeles County 2007–2012: Is there a measurable effect of the 2008 “Fast-Food Ban”? *Social science & medicine* 2015; **133**: 205-11.
377. Shannon J. What does SNAP benefit usage tell us about food access in low-income neighborhoods? *Social Science & Medicine* 2014; **107**: 89-99.
378. Shively G, Thapa G. Markets, Transportation Infrastructure, and Food Prices in Nepal. *Am J Agr Econ* 2017; **99**(3): 660-82.
379. FAO. Integration of nutrition in agriculture extension services in Africa. Rome: Food and Agriculture Organization of the United Nations, 2017.
380. FAO, WHO. ICN2 International Conferenc on Nutrition: better nutrition, better lives. 19-21 November 2014, Rome. http://www.fao.org/about/meetings/icn2/en/. Rome: Food and Agriculture Organisation, 2014.
381. TEEB AgriFood. Scientific and economic foundations report for the economics of ecosystems and biodiveristy (TEEB) for agriculture and food. Geneva: UN Environment Programme, 2018.
382. Niebylski ML, Redburn KA, Duhaney T, Campbell NR. Healthy food subsidies and unhealthy food taxation: A systematic review of the evidence. *Nutrition* 2015; **31**(6): 787-95.
383. Springmann M, Mason-D/'Croz D, Robinson S, et al. Mitigation potential and global health impacts from emissions pricing of food commodities. *Nature Clim Change* 2017; **7**(1): 69-74.

384. Thow AM, Jan S, Leeder S, Swinburn B. The effect of fiscal policy on diet, obesity and chronic disease: a systematic review. *Bulletin of the World Health Organization* 2010; **88**(8): 609-14.
385. Alderman H. Leveraging social protection programs for improved nutrition: summary of evidence prepared for the Global Forum on Nutrition-Sensitive Social Protection Programs, 2015. Washington, DC: International Bank for Reconstruction and Development/The World Bank, 2016.
386. Frelat R, Lopez-Ridaura S, Giller KE, et al. Drivers of household food availability in sub-Saharan Africa based on big data from small farms. *Proceedings of the National Academy of Sciences* 2016; **113**(2): 458-63.
387. HLPE. Price volatility and food security. Rome: Committee on World Food Security, 2011.
388. Torero M. Alternative mechanisms to reduce food price volatility and price spikes: policy responses at the global level. In: Kalkuhl M, Von Braun J, Torero M, eds. Food price volatility and its implications for food security and policy: Springer; 2016.
389. WHO. Global action plan for the prevention and control of NCDs 2013-2020. Geneva: World Health Organization, 2013.
390. United Nations General Assembly (UNGA). High Level Meeting on Prevention and Control of Non-communicable Diseases. 2011; New York, NY; 2011.
391. WHO. Set of recommendations on the marketing of foods and non-alcoholic beverages to children. Geneva: World Health Organization 2010.
392. WHO. Report of the Commission on Ending Childhood Obesity. Geneva: World Health Organization, 2016.
393. Swinburn B, Sacks G, Vandevijvere S, et al. INFORMAS (International Network for Food and Obesity/non-communicable diseases Research, Monitoring and Action Support): overview and key principles. *Obesity reviews : an official journal of the International Association for the Study of Obesity* 2013; **14 Suppl 1**: 1-12.
394. Garnett T, Mathewson S, Angelides P, Borthwick F. Policies and actions to shift eating patterns: what works? London: Food Climate Research Network, Chatham House, 2015.
395. Gonzalez-Fischer C, Garnett T. Plates, pyramids and planets. Developments in national healthy and sustainable dietary guidelines: a state of play assessment: FAO, University of Oxford, 2016.
396. Mason P, Lang T. Sustainable Diets: How Ecological Nutrition can Transform Consumption and the Food System. Abingdon: Routledge Earthscan; 2017.
397. WWF. One Planet Plate - Meals for a Living Planet. 2017. http://www.wwf.se/wwfs-arbete/mat/one-planet-plate/1728842-one-planet-plate-start (accessed 12 March 2018).
398. Ranganathan J, Vennard D, Waite R, et al. Shifting Diets for a Sustainable Future. . Washington, DC: World Resources Institute, 2016.
399. Culinary Institute of America, Harvard School of Public Health. Menus of Change Initiative. 2013. http://www.menusofchange.org/
400. Chefs Manifesto. Food is life: the global goals. Stockholm: Chefs Manifesto Network, 2017.
401. Relais et Chateau, UNESCO. Le Manifeste: un monde meilleur, par la table et l'hospitalité. Paris: Relais et Chateau, 2014.
402. Nordic Co-operation. The new Nordic food manifesto. 2004. http://www.norden.org/en/theme/ny-nordisk-mad/the-new-nordic-food-manifesto.
403. Sustainable Restaurants Association. One planet plate. London: SRA, 2018.
404. Mennella JA, Jagnow CP, Beauchamp GK. Prenatal and postnatal flavor learning by human infants. *Pediatrics* 2001; **107**(6): e88-e.
405. Birch LL. Development of food acceptance patterns in the first years of life. *Proceedings of the Nutrition Society* 1998; **57**(4): 617-24.

406. Hawkes C, Friel S, Lobstein T, Lang T. Linking agricultural policies with obesity and noncommunicable diseases: a new perspective for a globalising world. *Food Policy* 2012; **37**(3): 343-53.
407. Development Initiatives. Global Nutrition Report 2017: nourishing the SDGs. Bristol, UK: Development Initiatives, 2017.
408. Fung TT, Isanaka S, Hu FB, Willett WC. International food group–based diet quality and risk of coronary heart disease in men and women. *Am J Clin Nutr* 2018; **107**(1): 120-9.
409. IFPRI. Improving diet quality and micronutrient nutrition. Washington, DC: International Food Policy Research Institute, 2009.
410. Herrero M, Thornton PK, Power B, et al. Farming and the geography of nutrient production for human use: a transdisciplinary analysis. *The Lancet Planetary Health* 2017; **1**(1): e33-e42.
411. Gillespie S, van den Bold M. Agriculture, food systems, and nutrition: meeting the challenge. *Global Challenges* 2017.
412. Dangour AD, Hawkesworth S, Shankar B, et al. Can nutrition be promoted through agriculture-led food price policies? A systematic review. *BMJ open* 2013; **3**(6): e002937.
413. Smith J, Sones K, Grace D, MacMillan S, Tarawali S, Herrero M. Beyond milk, meat, and eggs: Role of livestock in food and nutrition security. *Animal Frontiers* 2013; **3**(1): 6-13.
414. Herrero M, Havlík P, Valin H, et al. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences* 2013; **110**(52): 20888-93.
415. Eating Better Alliance. Eating better for a fair green healthy future. http://www.eating-better.org/ (accessed November 29 2017).
416. Brauman KA, Siebert S, Foley JA. Improvements in crop water productivity increase water sustainability and food security—a global analysis. *Environmental Research Letters* 2013; **8**(2): 024030.
417. Altieri MA, Nicholls CI. The adaptation and mitigation potential of traditional agriculture in a changing climate. *Climatic Change* 2017; **140**(1): 33-45.
418. Muluneh A, Stroosnijder L, Keesstra S, Biazin B. Adapting to climate change for food security in the Rift Valley dry lands of Ethiopia: supplemental irrigation, plant density and sowing date. *The Journal of Agricultural Science* 2017; **155**(5): 703-24.
419. Geerts S, Raes D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural water management* 2009; **96**(9): 1275-84.
420. Fisher M, Abate T, Lunduka RW, Asnake W, Alemayehu Y, Madulu RB. Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in eastern and southern Africa. *Climatic Change* 2015; **133**(2): 283-99.
421. Du T, Kang S, Zhang J, Davies WJ. Deficit irrigation and sustainable water-resource strategies in agriculture for China’s food security. *Journal of experimental botany* 2015; **66**(8): 2253-69.
422. Seufert V, Ramankutty N, Foley JA. Comparing the yields of organic and conventional agriculture. *Nature* 2012; **485**: 229.
423. Robertson GP, Vitousek PM. Nitrogen in agriculture: balancing the cost of an essential resource. *Annual review of environment and resources* 2009; **34**: 97-125.
424. Castellanos-Navarrete A, Tittonell P, Rufino MC, Giller KE. Feeding, crop residue and manure management for integrated soil fertility management–A case study from Kenya. *Agricultural Systems* 2015; **134**: 24-35.
425. Chadwick D, Wei J, Yan'an T, Guanghui Y, Qirong S, Qing C. Improving manure nutrient management towards sustainable agricultural intensification in China. *Agriculture, Ecosystems & Environment* 2015; **209**: 34-46.
426. Schoumans O, Chardon W, Bechmann M, et al. Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: a review. *Science of the Total Environment* 2014; **468**: 1255-66.

427. Cerdà A, González-Pelayo Ó, Giménez-Morera A, et al. Use of barley straw residues to avoid high erosion and runoff rates on persimmon plantations in Eastern Spain under low frequency–high magnitude simulated rainfall events. *Soil Research* 2016; **54**(2): 154-65.
428. Nesme T, Colomb B, Hinsinger P, Watson CA. Soil phosphorus management in organic cropping systems: from current practices to avenues for a more efficient use of P resources. Organic farming, prototype for sustainable agricultures: Springer; 2014: 23-45.
429. Meers E. EIP-AGRI Focus Group on Nutrient Recyling: Starting Paper on how to improve the agronomic use of recycled nutrients (N and P) from livestock manure and other organic sources. 2016.
430. VanderZaag A, Amon B, Bittman S, Kuczyński T. Ammonia abatement with manure storage and processing techniques. Costs of Ammonia Abatement and the Climate Co-Benefits: Springer; 2015: 75-112.
431. Mao C, Feng Y, Wang X, Ren G. Review on research achievements of biogas from anaerobic digestion. *Renewable and Sustainable Energy Reviews* 2015; **45**: 540-55.
432. Good AG, Beatty PH. Fertilizing nature: a tragedy of excess in the commons. *Plos Biol* 2011; **9**(8): e1001124.
433. Norton R, Davidson E, Roberts T. Nitrogen use efficiency and nutrient performance indicators. *Global Partnership on Nutrient Management* 2015.
434. Kanter DR, Zhang X, Mauzerall DL. Reducing nitrogen pollution while decreasing farmers' costs and increasing fertilizer industry profits. *J Environ Qual* 2015; **44**(2): 325-35.
435. European Commission. Report from the Commission to the Council and the European Parliament on the implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources based on Member State reports for the period 2008-2011. Brussels; 2013.
436. Dorward A, Chirwa E. The Malawi agricultural input subsidy programme: 2005/06 to 2008/09. *International journal of agricultural sustainability* 2011; **9**(1): 232-47.
437. Druilhe Z, Barreiro-Hurlé J. Fertilizer subsidies in sub-Saharan Africa: ESA Working paper, 2012.
438. Griscom BW, Adams J, Ellis PW, et al. Natural climate solutions. *Proceedings of the National Academy of Sciences* 2017; **114**(44): 11645-50.
439. Ricketts TH, Daily GC, Ehrlich PR, Michener CD. Economic value of tropical forest to coffee production. *P Natl Acad Sci USA* 2004; **101**(34): 12579-82.
440. Klein AM, Steffan-Dewenter I, Tscharntke T. Pollination of Coffea canephora in relation to local and regional agroforestry management. *Journal of Applied Ecology* 2003; **40**(5): 837-45.
441. Porter-Bolland L, Ellis EA, Guariguata MR, Ruiz-Mallén I, Negrete-Yankelevich S, Reyes-García V. Community managed forests and forest protected areas: An assessment of their conservation effectiveness across the tropics. *Forest Ecology and Management* 2012; **268**(Supplement C): 6-17.
442. Robinson BE, Holland MB, Naughton-Treves L. Does secure land tenure save forests? A meta-analysis of the relationship between land tenure and tropical deforestation. *Global Environmental Change* 2014; **29**: 281-93.
443. Ostrom E, Nagendra H. Insights on linking forests, trees, and people from the air, on the ground, and in the laboratory. *Proceedings of the National Academy of Sciences* 2006; **103**(51): 19224-31.
444. Lambin EF, Meyfroidt P, Rueda X, et al. Effectiveness and synergies of policy instruments for land use governance in tropical regions. *Global Environmental Change* 2014; **28**: 129-40.
445. Bennett EM, Peterson GD, Gordon LJ. Understanding relationships among multiple ecosystem services. *Ecology letters* 2009; **12**(12): 1394-404.
446. de Waroux YIP, Garrett RD, Heilmayr R, Lambin EF. Land-use policies and corporate investments in agriculture in the Gran Chaco and Chiquitano. *Proceedings of the National Academy of Sciences* 2016; **113**(15): 4021-6.

447. Phalan B, Green RE, Dicks LV, et al. How can higher-yield farming help to spare nature? *Science* 2016; **351**(6272): 450-1.
448. Chazdon RL, Brancalion PH, Lamb D, Laestadius L, Calmon M, Kumar C. A Policy-Driven Knowledge Agenda for Global Forest and Landscape Restoration. *Conservation Letters* 2017; **10**(1): 125-32.
449. Crouzeilles R, Ferreira MS, Chazdon RL, et al. Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. *Science Advances* 2017; **3**(11).
450. Convention on Biological Diversity. Aichi Biodiversity Targets. https://www.cbd.int/sp/targets/ (accessed 20 November 2017).
451. IUCN. Bonn Challenge. http://www.bonnchallenge.org/content/challenge (accessed 12 March 2018).
452. Soto D, Aguilar-Manjarrez J, Brugère C, et al. Applying an ecosystem-based approach to aquaculture: principles, scales and some management measures. *Building an ecosystem approach to aquaculture* 2008; **14**.
453. Staples D, Funge-Smith S. Ecosystem approach to fisheries and aquaculture: Implementing the FAO Code of Conduct for Responsible Fisheries. . Bangkok, Thailand: FAO Regional Office for Asia and the Pacific, 2009.
454. FAO. Code of Conduct for Responsible Fisheries. Rome: FAO, 1995.
455. Clark CW, Munro GR, Sumaila UR. Subsidies, buybacks, and sustainable fisheries. *Journal of Environmental Economics and Management* 2005; **50**(1): 47-58.
456. Sumaila UR, Lam VW, Miller DD, et al. Winners and losers in a world where the high seas is closed to fishing. *Scientific reports* 2015; **5**: 8481.
457. Crona BI, Daw TM, Swartz W, et al. Masked, diluted and drowned out: how global seafood trade weakens signals from marine ecosystems. *Fish and Fisheries* 2016; **17**(4): 1175-82.
458. Lipinski B, O'Connor C, Hanson C. SDG Target 12.3 on Food Loss and Waste: 2016 Progress Report. *Washington, DC: Champions* 2016; **12**.
459. CFS. Food losses and waste in the context of sustianable food systems. A report by the High Level Panel of Experts on Food Security an Nutrition of the Committee on World Food Security. Rome: FAO, 2014.
460. Gustavsson J, Cederberg C, Sonesson U, Van Otterdijk R, Meybeck A. Global food losses and food waste: extent, causes and prevention. Rome: FAO, 2011.
461. HLPE. Investing in smallholder agriculture for food security. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome: FAO, 2013.
462. FAO. Food Loss and Waste Reduction: agro-industries brief. Rome: FAO, 2015.
463. Sidhu K. Participation pattern of farm women in post harvesting. *Stud Home Comm Sci* 2007; **1**(1): 45-9.
464. Niles MT, Ahuja R, Barker T, et al. Climate change mitigation beyond agriculture: a review of food system opportunities and implications. *Renewable Agriculture and Food Systems* 2018: 1-12.
465. Gladek E, Fraser M, Roemers G, et al. The Global Food System: An Analysis - report to WWF. Amsterdam: WWF Netherlands, 2016.
466. WWF, Zoological Society of London. Living Blue Planet Report 2015: Species, habitats and human well-being. Gland, Switzerland: WWF and ZSL, 2015.
467. WWF-UK. Eating for 2 Degrees: New and Updated Livewell Plates. Godalming: WWF-UK, 2017.
468. Oxfam, Bailey R. Growing a Better Future: Food justice in a resource-constrained world. Oxford: Oxfam International, 2011.
469. Lymbery P. Dead Zone: where the wild things were. London: Bloomsbury; 2017.

470. D'Silva J, Webster J, editors. The Meat Crisis: Developing more sustainable ethical production and consumption. Abingdon: Routledge; 2017.
471. Levy BS, Patz JA. Climate Change, Human Rights, and Social Justice. *Annals of Global Health* 2015; **81**(3): 310-22.
472. UNSCN. Sustainable Diets for Healthy People and a Healthy Planet. Rome: UNSCN, 2017.
473. UN General Assembly. United Nations Framework Convention on Climate Change : resolution / adopted by the General Assembly, 1994.
474. WHO. WHO Framework Convention on Tobacco Control, 2003.